# How Important Is Research on Pollution Levels in Antarctica? Historical Approach, Difficulties and Current Trends

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## Contents

## List of Acronyms

| | |
|---|---|
| AFS | Atomic fluorescence spectrometry |
| CCAMLR | The Commission for the Conservation of Antarctic Marine Living Resources |
| CD | Conductometry detector |
| CFCs | Chlorofluorocarbons |
| CHLs | Chlordanes |
| COMNAP | Council of Managers of National Antarctic Program |
| CZE | Capillary zone electrophoresis |

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| | |
|---|---|
| DDD | Dichlorodiphenyldichloroethane |
| DDE | Dichlorodiphenyldichloroethane |
| DDT | Dichlorodiphenyltrichloroethane |
| DLCs | Dioxin-like compounds |
| ECD | Electron capture detector |
| GC-MS | Gas chromatography–mass spectrometry |
| GPC | Gel permeation chromatography |
| HBB | Hexabromobenzene |
| HCB | Hexachlorobenzene |
| HCFCs | Hydrochlorofluorocarbons |
| HCHs | Hexachlorocyclohexanes |
| HPLC | High-performance liquid chromatography |
| IC | Ion chromatography |
| ICP-AES | Inductively coupled plasma atomic emission spectrometry |
| ICP-MS | Inductively coupled plasma mass spectrometry |
| ICP-OES | Inductively coupled plasma optical emission spectrometry |
| IDMS | Isotope dilution mass spectrometry |
| LC-MS/MS | Liquid chromatography with tandem mass spectrometry detection |
| LOD | Limit of detection |
| LOQ | Limit of quantification |
| LRAT | Long-range atmospheric transport |
| NNA | Neuron activation analysis |
| OC | Organochlorine compound |
| OCP | Organochlorine pesticides |
| PAHs | Polycyclic aromatic hydrocarbons |
| PBDEs | Polybrominated diphenyl ethers |
| PCBs | Polychlorinated biphenyls |
| PCDDs | Polychlorinated dibenzodioxins |
| PCDFs | Polychlorinated dibenzofurans |
| PCNs | Polychlorinated naphthalenes |
| PFBS | Perfluorobutane sulfonate |
| PFHxA | Perfluorohexanoic acid |
| PFNA | Perfluorononanoic acid |
| PFOA | Perfluorooctanoic acid |
| PFOS | Perfluorooctanesulfonic acid |
| POPs | Persistent organic pollutants |
| QqQ | Triple quadrupole |
| SFC | Supercritical fluid chromatography |
| SML | Surface microlayer |
| TC | Thermal conductivity |
| TLC | Thin-layer chromatography |
| TOC | Total organic carbon |
| TOF | Time of flight analyzer |
| XRF | X-ray fluorescence |

Highlights

- Scientific interest in the issue of presence of pollutants in Antarctica steadily increasing since 1960.
- In various samples from Antarctica a variety of harmful pollutants were identified.
- The analytic methods, which are dedicated to determine POPs and metals in different matrices, need to be developed.
- Antarctica is prone to storage of POPs, which may also undergo remobilization processes.

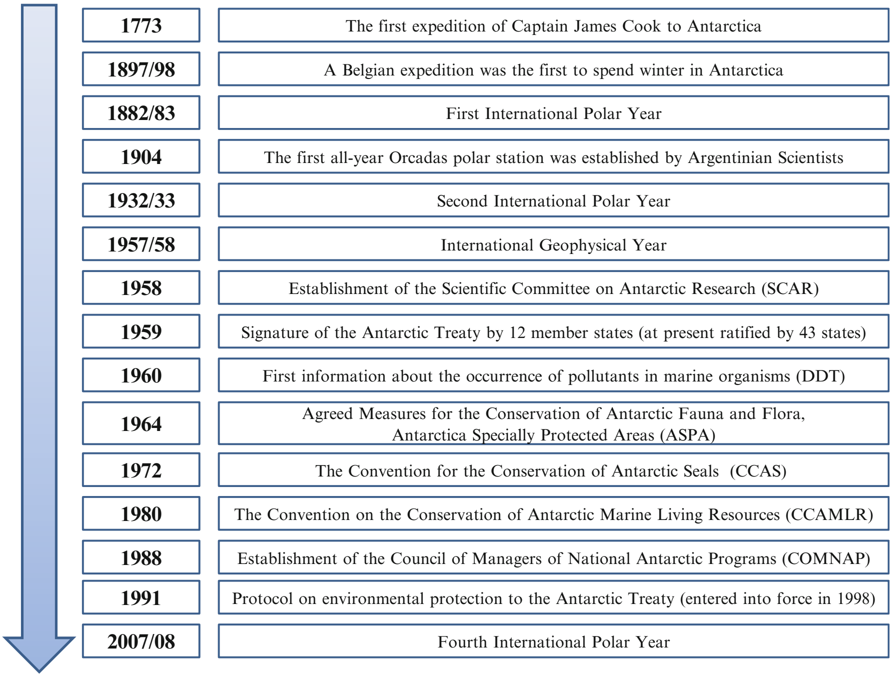
## 1 Introduction

The term "*Antarctica*" is used to define both the Antarctica continent itself as well as the Southern Ocean that surrounds the continent and the islands of this ocean. Antarctica is the most isolated continent; however, its specific location does not protect this area from negative impact of human activities (Aronson et al. 2011). A broad belt of the Southern Ocean's waters constitutes a barrier, which makes it difficult to transport pollutants this way. Therefore, volatile and semi-volatile chemical compounds may reach Antarctica together with air masses moving in this direction (long-range atmospheric transport—LRAT) (Corsolini 2009). However, more and more attention has been recently paid to the determination of the size of the locally emitted contamination impact on Antarctic environment (Bengtson Nash et al. 2011).

The first information on the occurrence of anthropogenic pollutants comes from the 1960s and it pertains to the presence of dichlorodiphenyltrichloroethane (DDT) in sea organisms (Bargagli 2008). Further research pertained to chemical composition of samples of water, snow and ice and it included metal and ion determination. Since the 1960s, research on the presences of pollutants from the group of persistent organic pollutants (POPs), e.g. hexachlorobenzene (HCB), hexachlorocyclohexanes (HCHs), aldrin, endrin, heptachlor and other pollutants in samples of living and non-living matter collected in Antarctica has been undertaken (Bargagli 2008; Corsolini 2009).

However, due to difficult climatic conditions, research pertaining to pollution analysis in this area was conducted on irregular basis. In recent decades, there has been a growing interest in the problems of pollutants present in samples from various elements of Antarctica's ecosystem. Figure 1 presents milestones of events influencing the development of research on Antarctica (including ones influenced development of chemical research).

Urbanised areas, especially those with intensive agriculture, as well as tropical and subtropical regions, where spraying is used for disease vector control, are the main sources of POPs and heavy metals in the Southern Hemisphere. The increase in the usage of many POPs has been observed in the 1990s in Asian countries and Southern Pacific islands (Bargagli 2008). Some large amounts of polychlorinated biphenyls (PCBs) used in older electrical devices were also deposited as landfill in some developing countries. The heaviest user of DDT, toxaphene and lindane, has



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|---|---|
| **1773** | The first expedition of Captain James Cook to Antarctica |
| **1897/98** | A Belgian expedition was the first to spend winter in Antarctica |
| **1882/83** | First International Polar Year |
| **1904** | The first all-year Orcadas polar station was established by Argentinian Scientists |
| **1932/33** | Second International Polar Year |
| **1957/58** | International Geophysical Year |
| **1958** | Establishment of the Scientific Committee on Antarctic Research (SCAR) |
| **1959** | Signature of the Antarctic Treaty by 12 member states (at present ratified by 43 states) |
| **1960** | First information about the occurrence of pollutants in marine organisms (DDT) |
| **1964** | Agreed Measures for the Conservation of Antarctic Fauna and Flora, Antarctica Specially Protected Areas (ASPA) |
| **1972** | The Convention for the Conservation of Antarctic Seals (CCAS) |
| **1980** | The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) |
| **1988** | Establishment of the Council of Managers of National Antarctic Programs (COMNAP) |
| **1991** | Protocol on environmental protection to the Antarctic Treaty (entered into force in 1998) |
| **2007/08** | Fourth International Polar Year |

**Fig. 1** Milestones of events connected with the development of Antarctic research (Köler 2013; SCAR Information; Dastidar and Ramachandran 2008; Dodds 2010)

historically been in South America. A comprehensive report by UNEP in 2002 gives more precise data on air levels of POPs in the Southern Ocean and Antarctica (Bargagli 2008).

A critical comparison and discussion of results of the research conducted over decades is not easy, as over a period of more than 50 years, methods and techniques used for research have undergone continuous changes. Moreover, while conducting research on such a complex ecosystem, it is necessary to frequently verify any possible changes by comparing the data acquired during different research projects and at different times. However, this task often cannot be practiced as the results may be achieved with the use of analytical techniques which present extremely different degrees of accuracy and sensitivity (Magi and Tanwar 2014).

The study presents information on the dynamics of the development of polar research (covering main groups of pollutants) both in terms of its methodology and the scope of research on Antarctica (diversity of tested samples and analytes) conducted over the past decades by members of teams working at polar research stations.

## 2 The Presence of Pollutants in Antarctica's Environment

Polar ecosystems consist of several key species. Mutual relationships between individual elements of the environment are closely connected; therefore, the presence of pollutants in one of elements of the ecosystem may have a significant influence on the functioning of the other ones. To become familiar with the influence of pollutants on the functioning of Antarctica's ecosystem, research is conducted on both abiotic and biological samples.

## *2.1 Abiotic Environment*

Abiotic environmental media (fresh water and seawater, precipitation, glaciers, soils, etc.), as well as all processes and phenomena connected with changes occurring in individual elements of the environment (meteorological, geological, geochemical processes, etc.), play a significant role in transporting pollutants in Antarctica (Cipro et al. 2012). Elements of abiotic environmental media, such as snow, glaciers and polar catchment areas are sources of water for all organisms living in Antarctica. Antarctica's ecosystem has a very simple structure, therefore, even a small amount of pollution present in abiotic elements of nature may constitute a significant hazard for any individual plant and animal species because of absence of advanced detoxification mechanisms (Bengtson Nash et al. 2011).

### 2.1.1 Air

The atmosphere plays an important role in transport of pollutants to polar areas. Over the past decade, a range of research has been conducted to determine mechanisms, which contribute to the presence of pollutants in Antarctica, as well as to distinguish between local sources of pollution and long-range atmospheric transport.

Information about Antarctica's air pollutants mostly comes from research conducted during cruises near Antarctica (Bengtson Nash et al. 2011) and is predominantly based on short-term (weeks–month) atmospheric monitoring (Kallenborn et al. 2013). Some of these data have been included in the assessment of global distribution of numerous POPs. However, due to the limited number of samples and non-continuous measurement periods, it is difficult to compare the results of air sample research conducted in Antarctica with the results of sample research from the Arctic region. A long-term atmospheric pollution monitoring in the polar regions is a significant scientific tool for assessing anthropogenic influences on the environment on a global scale. It enables the control or even changes of international legal regulations (Kallenborn et al. 2013).

The results of research on long-term monitoring of POPs were published in 2013 and focused on the concentrations of long-range transported contaminants (POPs) in the Antarctic environment. The research has revealed that the atmospheric long-range transport of polluted air masses is considered as the main source for the POPs monitored at Norwegian Troll station in Dronning Maud Land (Kallenborn et al. 2013). In the discussion about the presence of more volatile substances in Antarctica, as a source of it, long-range atmospheric transport is considered, while the presence of less volatile substances, which occur occasionally in Antarctic's air, may rather indicate influence of local sources (Kallenborn et al. 2013). A particular impact of local sources is shown in the analysis of compounds from the polybrominated diphenyl ethers (PBDEs) group. Due to the fact that neither plastics nor PBDE manufacturing occur in Antarctica, the substantial indoor PBDE residues are likely to originate from losses of imported flame retarded plastic and electronic products. There are plenty of electronic devices in the research stations, but at the same time there is not much space for them. Moreover, the material transport to Antarctica is expensive (Hale et al. 2008). The first atmospheric measurement, which was constructed as a part of a new continuous monitoring effort, was presented in one of Australia's all-year research station—Casey Station (66°17′ S 110°3′ E). The results suggest a potential local source of the currently produced, involatile, decabrominated PBDE congener 209, which contributes to PBDE profiles in all the samples (Bengtson Nash et al. 2011).

These discussions prove that it is necessary to take additional precautions in order to stop further deterioration of the pristine air status in Antarctica caused by the human presence in this region.

### 2.1.2 Snow and Ice

In polar areas chemicals like POPs have been observed in seasonal snowpack and in older layers of firn and ice, providing accumulation time series (Herbert et al. 2006b).

During long-range atmospheric transport, pollutants may undergo decomposition and deposition processes, depending on the physicochemical properties of individual compounds.

The mechanisms of exchange of trace organic contaminants between the atmosphere and snow (both falling snow and standing snowpack) depend on the major processes like scavenging (vapour and particle) by falling snow, vapour sorption/desorption to the snow's surface, and diffusion of chemicals both into and out of the snowpack (Herbert et al. 2006b). These processes dictate the quantities of chemical compounds available to meltwater and in deeper areas (permanent snow and ice). Additionally, processes occurring after deposition, e.g. snow settling (fresh snow is gradually transformed into firn and then in a glacier layer, the volume of which becomes gradually reduced) are of importance. The snow-settling process is the first stage, during which compounds, e.g. from the polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) group, are adsorbed on snowflakes. These compounds due to their physicochemical properties are classified as semi-volatile compounds, may become released back to the gaseous phase during seasonal snowmelt or diffused into deeper snow layers (Wania 1997). This process *inter alia* depends on solubility (concentration of a given compound), the snow-air partitioning properties and the temperature gradient. The snow-air partitioning properties not only depend on the vapour pressure but also on the surface properties of the snow flakes/snow pack. These properties largely determine the sorption and diffusion processes (Herbert et al. 2006b).

Based on experimental diffusivities for a volatile tracer of sulfur hexafluoride in snowpack it was concluded that in the low-wind (up to 3 m/s) scenario the migration of sulfur hexafluoride in the snowpack can be largely attributed to diffusive transport, while at high wind speeds (up to 9 m/s) the chemical migration is largely due to advective transport (Albert and Shultz 2002). Snow and firn metamorphism processes depend on the temperature fluctuations. Grain growth may occur, which, in turn, increases the firn permeability. As a result of global migration of a broad range of compounds towards higher latitudes, they become accumulated in polar regions (Kozak et al. 2013). Systematic compound accumulation contributes to the formation of a pollutant reservoir. A large part of the pollutant load is stored in snow and ice. Chemical compounds, which may be trapped in polar areas, can constitute a long-term hazard due to the possibility of their subsequent release into the environment—the so-called reemission into the environment may occur (Herbert et al. 2006a). Quantities of pollutants released during the spring snowmelt could have significant influence on the quantities of pollutants present in both freshwater and marine system (Herbert et al. 2006b). This hypothesis is named "spring pulse" and currently researchers are working on the creation of snowmelt models concerning quantitative transport of pollutants from snow to other abiotic environmental media (Burniston et al. 2007; Herbert et al. 2006b; Wania et al. 1999).

### 2.1.3 Soil and Permafrost

For the study of air transported pollutants, soil samples are worthy of note materials because of their direct contact with the atmosphere. Antarctica's soil may become polluted as a result of wet and dry deposition (LRAT) and accidental release of pollutants into the environment (oil spills) (Curtosi et al. 2007; Webster et al. 2003; Aisable et al. 2004).

The concentration limits of compounds in soil depend on the type of soil. Antarctica's soil variability is mainly due to parent material, differences in land-surface age (range: from a few thousand to millions of years), topographic position and local climate (Aisable et al. 2004).

In general approach to the presence of pollutants in soil, permafrost and an active soil layer play an important role in migration of compounds in soil (Curtosi et al. 2007). An active soil layer and permafrost presence is a unique characteristic of polar areas. It is known that repeated freeze/thaw cycles occur in areas with an active layer of permafrost, as a result of which soil particles may undergo a slow process of screening. Small particles may migrate from the surface layer into deeper layers, while stones have a tendency to migrate from deeper layers to the surface. Pollutants are adsorbed mostly from the surface of particles with a smaller diameter. Research results show that the percentage (quantity) of small particles and their dynamics in the soil matrix are the key factors in determining the fate and degradation of pollutants, e.g. PAHs in Antarctic soil. In this way, thawing of the upper layer of the permafrost, which may be caused by global warming, will have widespread influence on the distribution of pollutants in this environment (Curtosi et al. 2007).

### 2.1.4 Catchment Areas

There are lakes and small streams, which thaw in the summer in small areas of Antarctica which are free from ice. Open water lakes in Antarctica are very rare due to low temperatures. However, the accumulation of pollutants also occurs in lakes and lake sediments. Much higher concentrations (as compared to concentrations of the same analytes in soil samples) of some compounds, e.g. HCH in lake sediments are probably determined by the nature of Antarctic lakes. Antarctic's lakes are formed from melting ice water, which is rich in atmospheric particles (trapped in it during formation) (Fuoco et al. 2009a; Vandal et al. 1998).

Another factor, which influences the level of pollutants in freshwater environment, is the transport of persistent chemicals by seabirds biovector. Higher concentration of POPs has been recorded in aquatic organisms from a seabird-affected lake. This is a proof that seabird-transported contaminants have been entering freshwater and thereby local food webs (Michelutti et al. 2010; Xie and Sun 2008). As long as detailed mechanism of pollution transfer by seabird's vectors are not widely described, further researches should be applied in this direction.

### 2.1.5 Ocean, Seas and Bottom Sediments

Oceans and seas plays a significant role in the circulation and removal of pollutants. Within Antarctica, the Antarctic Convergence Zone (also called the Antarctic Polar Front) is distinguished. It runs between 47°S and 62°S. It separates cold and less saline Antarctic waters from subantarctic waters. The zone may be the barrier for pollutants transported by sea (Bengtson Nash et al. 2011).

Relatively much attention was devoted to research targeted at estimating the degree of exchange of pollutants between the seawater surface (inter-phase) and the atmosphere and the role of seawater in the process of transporting chemical compounds to polar regions. The sea surface consists of layers, out of which the sea surface microlayer (SML) has been researched most broadly (0.1–0.001 mm). This is a place where pollutants, atmospheric particles and microorganisms accumulate. However, the majority of research projects focusing on measurements of pollutant content in SML samples were conducted using samples collected in coastal environments. There is very little data from open ocean samples (Fuoco et al. 2009a).

Another element of abiotic environmental media in the pollutant transportation process is bottom sediments. More hydrophobic organic compounds may undergo sorption on solid particles and microorganisms. Dead particles of organic matter and solid particles settle on the bottom and, thus, pollutants adsorbed on them accumulate in bottom sediments (Boutron et al. 1990). Pollutants present in bottom sediments may be re-emitted as a result of activity of bottom organisms and ocean currents. Thus, the bottom sediments can become secondary source of pollution.

## *2.2 Biotic Environment*

Anthropogenic pollutants have an adverse effect on living organisms. Antarctic biota (e.g. seals and penguins) are particularly sensitive to contaminants. The natural stress on wildlife in extreme polar environments is often more severe than in temperate regions. Hence Antarctic species can be more vulnerable to the effects of pollutants in comparison with species which come from temperate regions (Schiavone et al. 2009a). Moreover, due to very simple structures of polar ecosystems, relationships between individual organisms are important in terms of pollution transfer. Mutual connections between individual species determine the way, in which pollutants are transported (Cipro et al. 2012).

### 2.2.1 Plants

Mosses and lichens are the main components of the terrestrial flora of Antarctica's ecosystem. Bryophytes are predominantly useful for monitoring the atmospheric pollution (metals and organochlorine compounds) because they have no protective waxy cuticles and no root system (Borghini et al. 2005). The content of pollutants present in samples of these plants largely depends on precipitation. Thus, they can play a very important role of biomonitors, i.e. indicators of long-term pollutant deposition (Fuoco et al. 2009a).

As mentioned above, pollutants present in the air may undergo dry or wet deposition, thus getting into Antarctica's environment. Plants absorb pollutants from the atmosphere (through their above-ground parts, especially leaves) or/and from the soil (through the roots). For compounds with strong hydrophobic properties, transport through solids seems to have little significance. Literature data may be the basis for concluding that the main mechanism of collecting pollutants from the environment is absorption from the surrounding air into the leaf surface of pollutants in the gaseous phase or the solid phase (through particles settled on plant surfaces) (e.g. Borghini et al. 2005; Mão de Ferro et al. 2014; Poblet et al. 1997; Wu et al. 2014; Yogui and Sericano 2008; Yogui et al. 2011). Pollutants get into plants through stomata or leaf epidermis. Furthermore, the process of "assimilating pollutants" into plants is influenced by a range of physicochemical factors (e.g. partial pressure of water vapour, the numerical value of the octanol/water partition coefficient and the water/octanol partition coefficient), environmental factors (e.g. the temperature, precipitation, wind speed) and plant properties (e.g. the species, fat content, leaf morphology) (Yogui and Sericano 2008; Yogui et al. 2011).

### 2.2.2 Crustaceans, Benthic Organisms and Fishes

Antarctica's ecosystem has a very simple structure. Organisms at higher levels of the trophic chain depend on several key species, such as the Antarctic silverfish (*Pleuragramma antarcticum*) and the Antarctic krill (*Euphausia superba*). The

Antarctic silverfish and the Antarctic krill are the main sources of food for many maritime species of birds and mammals. As a result of the mutual relationship between the size of the krill and silverfish populations and the size of the populations of other species, a decrease in the krill and silverfish population size may have a negative impact on the entire environment of Antarctica's marine ecosystem (Corsolini et al. 2002b). As a result of close relationships between individual species, POPs are present in every level of the trophic chain (Corsolini et al. 2002b). The phenomenon of biomagnification plays a more important role than bioaccumulation itself in the case of Antarctic fish. Lower pollutant concentrations are observed in samples of fish, for which krill is the staple food. Values of harmful compound concentrations increase if invertebrates or other fish are the main source of food (Weber and Goerke 2003).

In pelagic fish a downward trend in concentrations of some persistent organic pollutants (e.g. HCB, dieldrin) is visible (Van den Brink et al. 2011). It contrasts distinctly with steady or increasing concentrations levels in benthic organisms. Transfer of contaminants between Antarctic pelagic and benthic food webs is associated with seasonal sea-ice dynamics and thus with different climatic conditions. This fact may hinder the predictability of future trends of emerging compounds in the Antarctic ecosystem (e.g. the brominated compounds). The discrepancy in trends between pelagic and benthic organisms still remains the question whether the total environmental burden of contaminants in the Antarctic ecosystem is declining or increasing (Van den Brink et al. 2011).

### 2.2.3 Seabirds

Marine birds are another link in the food chain, where penguins constitute the most numerous group. They belong to key-species in Antarctica's ecosystem. Penguins feed mainly on krill and also on fish (depending on krill's accessibility). Researchers have reported that predators may be a sink for chemicals (special for volatile and toxic ones) and this may pose an important environmental problem (Corsolini et al. 2007).

Penguins (Adèlie and Emperor) spend their whole life in the Southern Ocean, while marine bird species, such as migrating snow petrel, south polar skua, brown skua are species migrating all over Antarctica. In both cases, results of samples researched from these species could reflect the condition of their ecosystems (Corsolini et al. 2011). The aforementioned bird species rely on all krill species and the Adèlie penguin eats the most krill (Corsolini et al. 2011). The Emperor penguin also eats a lot of fish as well as crustaceans and cephalopods. The south polar skua feeds on penguins' eggs and chicks and it also eats Antarctic silverfish krill (over 80 %). In the nesting season, on the other hand, skuas depend on food found on land. The brown skua also relies on sea food (Corsolini et al. 2011). Moreover, the research results concerning detection of POPs in seabirds' eggs (including penguin and south polar skua eggs) proved the transfer of POPs from mothers to eggs (Corsolini et al. 2002a).

The most important link between Antarctic marine, freshwater and terrestrial ecosystems constitutes seabirds. In fact, they maintain the development of terrestrial flora due to the high amount of nutrients deposited by seabirds on the land (e.g. by guano). Seabirds usually transport loads of pollution. Unfortunately, endocrine mechanisms are still poorly investigated in free-living organisms, despite the fact, that contaminants have endocrine disrupting properties. In the scientific literature there is surprisingly only few data on the effect of age on contaminant levels, despite the fact that long-lived organisms are thought to be highly sensitive to pollution. Therefore, it is not clear if seabirds accumulate POPs with increasing age (Tartu et al. 2015).

Comparing research results concerning pollution in birds' tissues from other areas of the world, shows that POPs concentrations in penguins are relatively low (Corsolini et al. 2007). In relation to species and sex, different chemical accumulation patterns are observed. Penguins are showing low detoxifying capacities and therefore studies on their xenobiotic metabolism should be carried out (Corsolini et al. 2007).

### 2.2.4 Marine Mammals

During the evaluation of contamination presence in the marine mammals' tissues scientists should bear in mind the migratory habits of these organisms. Some species of marine mammals (including cetaceans) exist in Antarctica' seawaters in summer time and then go northward during winter, while other species, e.g. some seals, spend their entire life cycles in the Southern Ocean and on the Antarctic coasts. In migrating organisms what may affect the amount of pollution in Antarctic organisms is the forage or breed during summer, as well as exposition to pollutants in more contaminated areas during winter. Species and individuals staying in anthropized areas during migration contribute to greater exposure to contamination compared with those that stay in Antarctica all year round. Furthermore, pollution (like POPs) accumulation in marine mammals depends on some other factors including metabolism (Corsolini 2009).

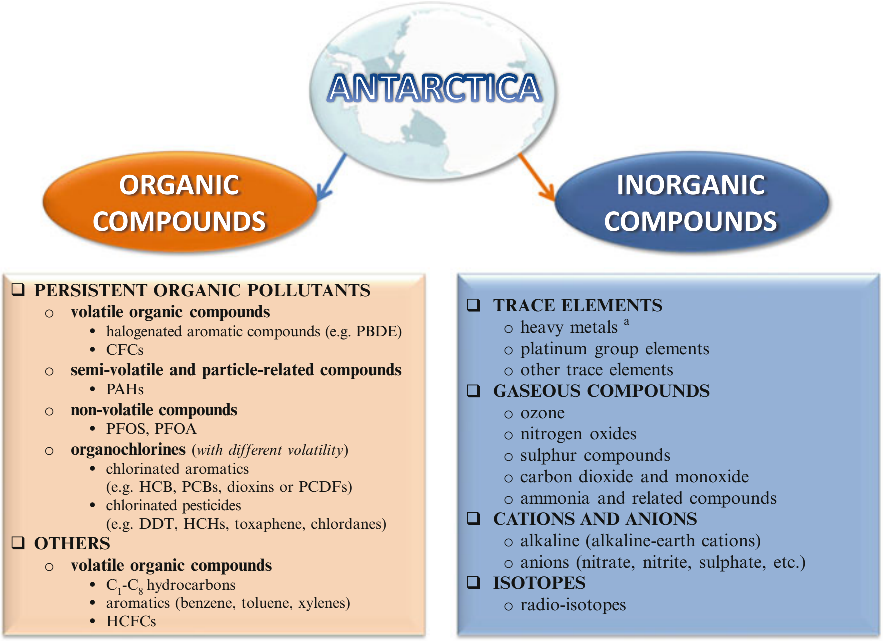
Marine mammals differ from the land ones with a high lactation transfer of all lipophilic substances (including pollutants) to young animals (Schiavone et al. 2009a; Trumble et al. 2012). This mostly results from an increased fat content in the mother's milk (Schiavone et al. 2009a). For cetacea and pinnipeds a vast majority (approx. 90 %), of the total amount of chloroorganic pollutants occurring in newborns are transferred in the mother's milk (Cipro et al. 2012). Due to the position of mammals in the trophic chain of the marine environment, a relatively long life and an increased demand for energy, the pinniped species can be treated as an indicator (reference) species for the examination of harmful effects of pollutant bioaccumulation in organisms (Cipro et al. 2012).

Marine mammals have been exposed also *inter alia* to heavy metals. Scientists are devoting particular attention to mercury because of its toxicity as well as the fact that it is widespread within the environment, and can be biomagnified in marine food chains. Very important is also the fact that Hg is available mainly because of human activities (e.g. Jerez et al. 2011). However, data of concentrations of Hg in seals and other vertebrates of Antarctica's are sparse (Szefer et al. 1993). Moreover, most of the attention in marine mammals' research is devoted to the identification of organic contaminants. Some reports lead even to observation of an increasing trend of PCBs and chlorinated pesticides: HCB, HCHs, chlordanes (CHLs), DDTs in minke whales (*Balaenoptera bonaerensis*) feeding on Antarctic krill between 1984/1985 and 1992/1993 (Aono et al. 1997). Concentration of DDTs, PCBs and HCB have been reported in various species of marine mammals during last decades. However, data on the presence of other POPs (including new emerging ones, like poly- and per fluorinated organic compounds (PFCs)), even if it was reported in oceanic and lake water samples (Cai et al. 2012), in marine mammals tissues are still scarce (Corsolini 2009).

Only a few of the hundreds of thousands of different industrial chemicals produced on a world scale have been studied and reported in the Antarctic environment. Antarctica's trophic chains are relatively simple and short and therefore understanding the detailed information on the levels of pollutants in different parts of the environment (including abiotic part) is very important. Animals at the top of the food webs depend on a few key species. Therefore affecting one of these key species could have a devastating impact on the whole ecosystem.

## 3 Types of Pollutants Present in Antarctica's Environment

Anthropogenic pollutants in Antarctica may come from global (LRAT) and local sources. Global sources include industrialised sites situated all over the Southern Hemisphere, from which pollutants are transported to Antarctica by various routes (Bargagli 2008). Local sources, on the other hand, include, amongst other things, scientific activities which are connected with the use of waste incineration plant, fuel consumption, sewage production, developing tourism and related intensification of ship transport (Cincinelli et al. 2009). The most polluted areas include areas around historic bases and polar stations where soil is often polluted by fuel remains, solid waste and household sewage (Negri et al. 2006; Webster et al. 2003). Anthropogenic pollutants are present in various elements of the environment in Antarctica. Because of their specific (also hazardous) properties POPs and heavy metals are described in this article in detail. However, authors do not include any chapter about general sources, properties and toxicity of pollutant groups determined in various types of samples collected from the Antarctic environment. This information has been given in other literature sources (e.g. Aisable et al. 2004; Borghesi et al. 2008; Cincinelli and Dickhut 2011; Corsolini 2009; Fuoco et al. 2012; Houde et al. 2011; Ma et al. 2014; Planchon et al. 2002; Vecchiato et al. 2015).



[a]including mercury itself and its transformation products (e.g. methylmercury-organic compound)

**Fig. 2** The group of chemical compounds identified in Antarctica

Despite the fact that environmental studies represent only a small part of scientific research in Antarctica (Magi and Tanwar 2014), polar explorers are increasingly also interested in chemical research. Figure 2 shows a group of chemical compounds that are of interest to researchers in Antarctica (after Walton et al. 2001).

In the discussion on the presence of organic compounds in the Antarctic environment, scope of interest is mainly focused on POPs like HCB, PCBs, DDTs, PBDE and PAHs. Over the past decades, sporadic research also pertained to identification and determination of compounds such as: CHL, dioxins, dioxin-like compounds (DLCs), PFCs, pesticides (dieldrin, mirex, heptachlor, endosulfan), aliphatic hydrocarbons, n-alkanes and cumulative parameters such as total organic carbon (TOC) in various environmental samples.

The presence of metals in remote Antarctica is not, as it was thought previously, limited only to lead and copper, but also other includes metallic elements, metalloids and radioactive elements, such as: V, Cr, Mn, Zn, Co, Ag, Cd, Ba, Bi, U, Pt, Ir, Rh, Mo, Tl, As, Sb (Hong et al. 2012; Soyol-Erdene et al. 2011).

# 4 Detailed Information Pertaining to Analytical Research in Antarctica

For a long time Antarctica was not available to scientists mainly because of the specificity of its location. Initial research was aimed at getting to know geological properties of the area. With time, also meteorological, magnetic and botanic research was undertaken and in recent years, chemical research was also conducted. The implementation of this research requires enormous involvement and determination on the part of scientists, mostly due to very difficult weather conditions (Köler 2013).

## 4.1 *History of Research on the Chemical Composition of Samples from Antarctica*

Research conducted in Antarctica has always been interdisciplinary. One area of research includes actions connected with determining the chemical composition of biotic and abiotic samples. Initially, it was research using classical analytical techniques; however, the scope of determined compounds has been expanded over time. Table 1 presents the historical calendar pertaining to the development of the scope of analytical research of the Antarctic environment conducted up to the end of 1989.[1]

## 4.2 *Pollution Concentration Levels Over Decades*

The scope of analytical researches conducted over individual decades is differentiated both in respect of the place of research and types of samples and analytes which are determined in them. Monitoring of the environment allows for reliable observation changes and information contained in publications pertain to individual parts of the Antarctic ecosystem and various groups of pollutants. At present, scientists devote a lot of attention to research on pollutant levels in Antarctica's environment; however, there are still areas which have not been researched in this respect. Figure 3 shows the percentage of most commonly studied regarding the presence of contaminants in the environment of Antarctica up to end of 2014.

In this article, the authors pay particular attention to the research on determination of persistent organic compounds and heavy metals in different samples from

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[1] Analytical research is applied in Antarctic since the early 1960s. (that gives 55 years period of research). Hence authors decided to designate first three decades as historic ones (up to the end of 1989). During this period only few data has been published, hence this period is three decades long.

**Table 1** Historical calendar pertaining to the development of the scope of analytical research of the Antarctic environment conducted up to the end of 1989

| Year | Sampling place | Analytes or subject of research | Type of sample | The analytic techniques | Literature |
|---|---|---|---|---|---|
| 1960 | n/a[a] | DDTs | Adelie penguins, crabeater seal | n/a | Bargagli (2008) |
| 1963 | Princess Elizabeth Land | Trace metals: Sr, Br, | Lake water | n/a | Burton (1981) |
| 1964 | South Victoria Land | Element: I | Lake water | n/a | Burton (1981) |
| 1966 | Mc Murdo Dry Valley | Chemical composition ($Cl^-$, $Mg^{2+}$, $Ca^{2+}$,C –biocarbonate ion concentration) temperature, density, solar radiation penetrating the ice, conductivity | Lake water | Classical analytical techniques (titration), selenium photo-electric cell, a bolometer, remote control conductivity probe | House et al. (1966) |
| 1967 | McMurdo Station, Hut Point Peninsula Saddle, Taylor Valley, Ross Ice Shelf, Mt. Discovery | $NO_2$, $SO_2$ aldehydes | Air | Portable air sampling apparatus | Fischer et al. (1967) |
| | South Victoria Land | Trace metals: Mn, Fe, Mo, Pb, Zn, Bi, Rb, Cs | Lake water | n/a | Burton (1981) |
| 1969 | Pacific Ocean | PCBs | Sea birds | n/a | Risebrough et al. (1969) |
| | Interior of The Antarctic Continent | Pollutant lead aerosols, terrestrial dusts and sea salts | Snow strata | n/a | Murozumi et al. (1969) |
| | Plateau Station | DDT | Surface snow | n/a | Peterle (1969) |
| 1972 | Mirny, Vostok | Cl, Na, Mg, K, Ca, Mg, Fe | Surface firn | Atomic absorption, neutron activation | Boutron et al. (1972) |
| | Doumer Island, Antarctic Peninsula | PCBs | Penguin eggs | n/a | Risebrough and Carmlgnani (1972) |
| 1975 | Halley Bay | DDT | Snow | n/a | Peel (1975) |
| 1976 | n/a | DDTs, PCBs | Snow penguin eggs | n/a | Aono et al. (1997), Risebrough et al. (1976) |

(continued)

**Table 1** (continued)

| Year | Sampling place | Analytes or subject of research | Type of sample | The analytic techniques | Literature |
|---|---|---|---|---|---|
| 1978 | East Antarctic, South Polar Station And Dome C | Sulfate $SO_4^{2-}$ | Snow | Classical analytical techniques (titration) | Delmas and Boutron (1978) |
| 1978/ 1979 | Ross Island and the Wrightand Taylor Valleys | Fe, Hg | Sediments, clays and rock fines | Atomic absorption spectrophotometry | Siegel et al. (1981) |
| 1980 | Mc Mundo | Environmental assessment of Antarctic research | Rocks, ice cores, soil samales, meteorites, certain biota, fossils | n/a | Myers et al. (1980) |
|  | King Edward Cove | Aliphatic hydrocarbons, PAHs | Plants, soil, fresh-water sediment, zooplankton | Gas chromatography-mass spectrometry (GC-MS) | Platt and Mackie (1980) |
|  | James Ross Island | Acidity | Precipitation | pH determination or titration | Delmas and Gravenhorst (1983) |
| 1981 | Signy Island, King Edward Cove | Aliphatic and aromatic hydrocarbons | Marine benthic invertebrates | n/a | Clarke and Law (1981) |
|  | Syowa Station | DDTs, PCBs | Fish (whole body) | Gas chromatography—electron capture detector (GC-ECD) | Subramanian et al. (1983) |
| 1982 | The Geographic South Pole | Na, Mg, K, Ca, Fe, Al, Mn, Pb, Cd, Cu, Zn and Ag | Snow layers | Atomic absorption techniques | Boutron (1982) |
| 1983 | n/a | DDTs, PCBs | Fish tissues | n/a | Aono et al. (1997) |
|  | Ross Sea | DDTs, PCBs | Weddell seal blubber | n/a | Aono et al. (1997) |
|  | East Antarctica | Pb | Snow cores | Isotope dilution mass spectrometry (IDMS) | Boutron and Patterson (1983) |
| 1984 | The Coast On Riiser-Larsenisen Ice Shelf | Ions (for example: $SO_4^{2-}$, $Na^+$) | Snow profiles | n/a | Gjessing (1984) |
|  | n/a | DDTs, PCBs | Mink whale liver, Ross seal blubber | n/a | Aono et al. (1997) |

| | | | | | |
|---|---|---|---|---|---|
| 1979 | Areas of the Antarctic ice cap | Heavy metals (Pb, Cd, Cu, Zn, Ag) | Snow | Atomic absorption techniques | Boutron (1979) |
| 1984 | n/a | Trace metals and chlorinated hydrocarbons | Ross seal tissues | Atomic absorption techniques, gas-liquid chromatograph fitted with ECD | McClurg (1984) |
| | East Antarctica | Cd, Cu, Zn, Au, Se, $SO_4^{2-}$ | Prehistoric ice | n/a | Boutron et al. (1984) |
| | n/a | $Na^+$, $NH_4^+$, $K^+$, $Cl^-$, $NO_3^-$, $SO_4^{2-}$ | Snow and ice | Ion chromatography (IC) | Legrand et al. (1984) |
| 1986 | Antarctic Peninsula | Chlorinated hydrocarbon residues (HCB, HCH isomers, p,p′ DDT, DDE, PCB congeners) | Lichen and moss samples | n/a | Bacci et al. (1986) |
| | Adelie Land | $Na^+$, $NH_4^+$, $K^+$, $Cl^-$ $NO_3^-$, $SO_4^{2-}$, $Mg^{2+}$ | Precipitation | IC | Legrand and Delmas (1986) |
| | n/a | DDTs, PCBs | Penguin tissues | n/a | Aono et al. (1997) |
| 1987 | Ross Sea, Wilkes Land | Normal alkanes (n-C-$C_{36}$), isoprenoid hydrocarbons (i-$C_{15}$, i-$C_{16}$, i-$C_{18}$, i-$C_{19}$, and i-$C_{20}$) triterpanes ($C_{27}$-$C_{32}$), and ($C_{27}$-$C_{29}$) | Quaternary sediment | n/a | Kvenvolden et al. (1987) |
| | Syowa Station, Antarctica | Heavy metals | Tissue of the Weddell seal | n/a | Yamamoto et al. (1987) |
| | n/a | $NH_4^+$, $F^-$, $COOH^-$, $CHOO^-$, $CH_3SO_3^-$, $F^-$, $NH_4^+$ ions | Ice | IC | Saigne et al. (1987) |
| 1988 | The South Shetland Islands | Pb | Aerosols | IDMS | Völkening et al. (1988) |
| | The Ekstrrm ice shelf, “Georg-von- Neumayer” station | Heavy metals | Surface snow | IDMS, differential pulse anodic stripping voltammetry (DPASV) | Völkening and Heumann (1988) |

(continued)

**Table 1** (continued)

| Year | Sampling place | Analytes or subject of research | Type of sample | The analytic techniques | Literature |
|---|---|---|---|---|---|
| | Weddell Sea, Antarctic Peninsula | $HNO_3$ | Surface snow | IDMS | Neubauer and Heumann (1988) |
| | Sections Of the Byrd Station | Liquid conductivity, acidity, sulfate, nitrate, aluminum, and sodium concentrations | Ice containing tephra (volcanic ash) layers | n/a | Palais (1988) |
| | Vostok Station | $Na^+$, $NH_4^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$, $H^+$, $Cl^-$, $NO_3^-$ $SO_4^{2-}$ | Ice core | n/a | Legrand et al. (1988) |
| | Mc Muurdo Sound | Fatty acids, -alcohols, n-alkanes, PAH | Marine sediments | n/a | Venkatesan (1988) |
| 1989 | n/a | Organochlorine pesticides, PCBs and mercury | Seabird eggs and tissues | n/a | Luke et al. (1989) |
| | The coastal area of Antarctica | $SO_4^{2-}/Na^+$, $SO_4^{2-}/Cl^-$, $SO_4^{2-}/Mg^{2+}$ | Snow | n/a | Gjessing (1989) |
| | Wright Valley, Antarctica | Mn, Fe, Co, Ni, Cu, Cd | Fresh water | n/a | Green et al. (1989) |

[a] no data

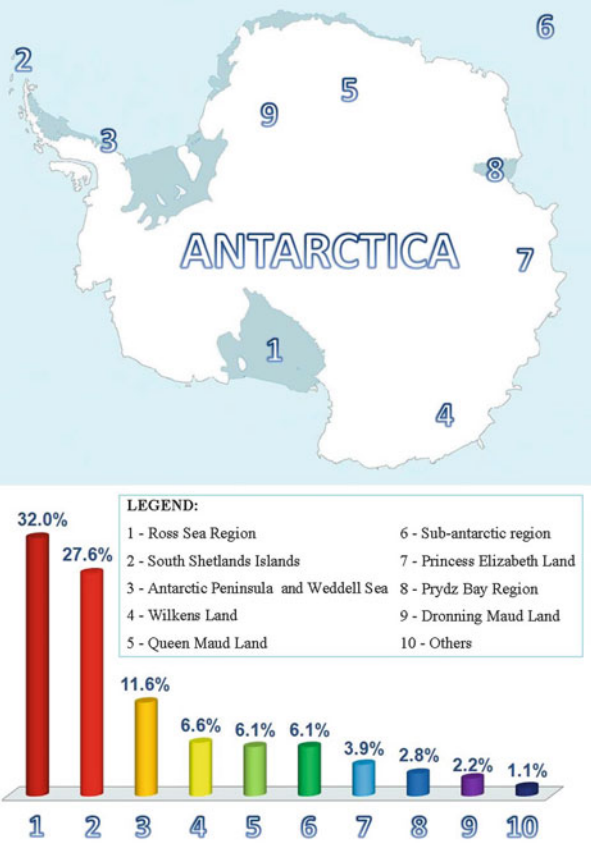

**Fig. 3** The percentage of areas most commonly studied regarding the presence of contaminants up to end of 2014 in the Antarctic environment

Antarctica because of the toxic properties and the threat which is associated with their presence in the polar environment. Table 2 presents general information on xenobiotics determined in samples collected from various parts of the Antarctic ecosystem.

In the discussion pertaining to the presence of pollutants in Antarctica, it is very important to become familiar with accurate levels of concentration present in individual elements of both, biotic and abiotic, environments. Table 3 (A, B, C) data referring to levels of detected contamination present in the whole Antarctic environment and Fig. 4 presents a summary of POPs and heavy metals concentration levels determined in various elements of Antarctica's environments during three time periods (up to end of 2014).

As is showed in Fig. 4 studies on the determination of the pollutants concentrations in biotic and abiotic samples over the decades are irregular. It makes presentation of concentrations trends very difficult. However, as a main source of air contamination the LRAT from Africa, South America or Australia (Negoita et al. 2003) is administered. Nevertheless, the year-round operation of stations

**Table 2** Summary of literature data on results of analytical research on various types of (a) abiotic and (b) biotic samples collected in Antarctica in three time periods

| Abiotic samples | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of sample | Time range within which the results were published | Analytes | | | | | | | | | | |
| | | OCP | | | | PCBs | PBDEs | PAHs | PFCs | Metals | Other[b] | Literature |
| | | DDTs | HCHs | HCB | Other[a] | | | | | | | |
| Air | Up to 1989 | x | | | | | | | | | x | Sen Gupta et al. (1996), Fischer et al. (1967) |
| | 1990–1999 | x | x | x | x | x | | x | | x | | Larsson et al. (1992), Kallenborn et al. (1998), Caricchia et al. (1995), Bidleman et al. (1993), Riidlein and Heumann (1995) |
| | 2000–2014 | x | x | x | x | x | x | | | x | x | Cincinelli et al. (2009), Cabrerizo et al. (2013), Galbán-Malagón et al. (2013a, c), Gambaro et al. (2005), Li et al. (2012), Choi et al. (2008), Montone et al. (2003), Baek et al. (2011), Montone et al. (2005), Kallenborn et al. (2013), Dickhut et al. (2005), Ma et al. (2014), Fischer et al. (2002), Sprovieri et al. (2002) |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Snow | Up to 1989 | x | x | | | x | | | | x | x | Kang et al. (2012), Sen Gupta et al. (1996), Delmas and Boutron (1978), Boutron and Patterson (1983), Wania et al. (1998), Boutron et al. (1972), Aono et al. (1997), Risebrough et al. (1976), Völkening and Heumann (1988) |
| | 1990–1999 | | | | | | | | | x | | Suttie and Wolff (1992), Görlach and Boutron (1992), Wolff et al. (1999), Vandal et al. (1995), Capelli et al. (1998). Vandal et al. (1998) |
| | 2000–2014 | | x | x | | x | x | x | x | x | x | Kang et al. (2012), Vecchiato et al. (2015), Fuoco et al. (2012), Nemirovskaya (2006), Antony et al. (2011), Cai et al. (2012), Zoccolillo et al. (2007), Edwards et al. (2001), Planchon et al. (2002), Planchon et al. (2001), Thamban and Thakur (2013), Fortner et al. (2011), Witherow and Lyons (2008), Han et al. (2013), Velde et al. (2005), Burn-Nunes et al. (2011), Vallelonga et al. (2010) |
| Ice | Up to 1989 | | | | | | | | | x | | Boutron et al. (1984) |
| | 1990–1999 | | | | | | | | | x | x | Green et al. (1992), Hong et al. (1998), Vandal et al. (1995) |
| | 2000–2014 | | | | | | | x | | x | | Nemirovskaya (2006), Vallelonga et al. (2010), Jiratu et al. (2009) |

(continued)

**Table 2** (continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fresh waters | Up to 1989 | x | x | | | | | x | | x | x | Sen Gupta et al. (1996), Burton (1981), Platt and Mackie (1980), Green et al. (1989) |
| | 1990–1999 | | | | | | | | | x | | Vandal et al. (1998) |
| | 2000–2014 | | | | | | | | x | x | x | Cai et al. (2012), Mão de Ferro et al. (2013) |
| Seawater | Up to 1989 | | | | | | | | | | x | Platt and Mackie (1980) |
| | 1990–1999 | | | | | | | | | x | x | Guerra et al. (2013), Stortini et al. (2009), Cripps (1992), Green et al. (1992), Niemistö and Perttilä (1995) |
| | 2000–2014 | x | x | x | | x | | x | x | | x | Cincinelli et al. (2009), Cincinelli et al. (2008), Stortini et al. (2009), Bicego et al. (1996), Galbán-Malagón et al. (2013b), Fuoco et al. (2009b), Zhang et al. (2013), Ahrens et al. (2010), Cai et al. (2012) |
| Polonya water | Up to 1989 | | | | | | | | | | | – |
| | 1990–1999 | x | x | | | x | | | | | | Sen Gupta et al. (1996) |
| | 2000–2014 | | | | | | | | | | | – |
| Sediments | Up to 1989 | | | | | | | x | | x | x | Platt and Mackie (1980), Venkatesan (1988), Merlin et al. (1989), Siegel et al. (1981) |
| | 1990–1999 | x | x | | | x | | | | x | x | Fuoco et al. (1996), Sen Gupta et al. (1996), Risebrough et al. (1990), Green et al. (1992), Vandal et al. (1998), |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Yuguang and Junlin (1991), Giordano et al. (1999), Ciaralli et al. (1998), Crespi et al. (1993), Niemistö and Perttilä (1995), Ahn et al. (1996), Alam and Sadiq (1993), Santos et al. (2005), Lenihan (1992) |
| | 2000–2014 | **x** | **x** | **x** | | **x** | | **x** | | **x** | **x** | Zhang et al. (2013), Klánová et al. (2008), Montone et al. (2001),<br>Curtosi et al. (2007),<br>Dauner et al. (2014),<br>Kim et al. (2006),<br>Negri et al. (2006), Crockett and White (2003),<br>Martins et al. (2010),<br>Siegel et al. (1981),<br>Santos et al. (2007),<br>Ribeiro et al. (2011),<br>Ribeiro et al. (2010),<br>Waheed et al. (2001),<br>Negri et al. (2006),<br>Ianni et al. (2010),<br>Huang et al. (2014),<br>Townsend and Snape (2008),<br>Sun et al. (2013),<br>Vodopivez et al. (2015),<br>Curtosi et al. (2010),<br>Andrade et al. (2001) |
| Soil | Up to 1989 | | | | | | | **x** | | | **x** | Platt and Mackie (1980) |
| | 1990–1999 | | **x** | **x** | | **x** | | **x** | | **x** | | Aislabie et al. (1999),<br>Mazzera et al. (1999),<br>Kennicutt et al. (1995), |

(continued)

**Table 2** (continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Fuoco et al. (1996), Carrasco and Prendez (1991),<br>Bargagli et al. (1995),<br>Bargagli et al. (1999) |
| | 2000–2014 | **x** | **x** | **x** | | **x** | | **x** | | **x** | | Borghini et al. (2005),<br>Klánová et al. (2008),<br>Cabrerizo et al. (2012),<br>Negoita et al. (2003),<br>Curtosi et al. (2007),<br>Kang et al. (2012),<br>Webster et al. (2003),<br>Lu et al. (2012) |

Biotic samples

| Type of sample | Time range within which the results were published | Analytes | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | OCP | | | | PCBs | PBDEs | PAHs | PFCs | Metals | Other[d] | Literature |
| | | DDTs | HCHs | HCB | Other[c] | | | | | | | |
| Krill | Up to 1989 | | | | **x** | | | | | **x** | **x** | Platt and Mackie (1980), Bargagli (2008), Moreno et al. (1997) |
| | 1990–1999 | **x** | **x** | **x** | **x** | **x** | | | | **x** | | Sen Gupta et al. (1996),<br>Aono et al. (1997),<br>Bargagli (2008),<br>Petri and Zauke (1993) |
| | 2000–2014 | **x** | **x** | **x** | **x** | **x** | **x** | | | **x** | | Corsolini et al. (2002a, b),<br>Corsolini et al. (2006),<br>Cincinelli et al. (2009),<br>Cipro et al. (2010), Senthil et al. (2002), Santos et al. (2006) |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zooplankton and phytoplankton | Up to 1989 | | | | x | | | x | | | x | Platt and Mackie (1980) |
| | 1990–1999 | | | | | | | | | | | – |
| | 2000–2014 | | x | x | | x | | | | x | | Bargagli (2008), Galbán-Malagón et al. (2013b) |
| Benthic organisms | Up to 1989 | | | | x | | | | | | x | Platt and Mackie (1980),<br>Clarke and Law (1981) |
| | 1990–1999 | | | | | | | | | x | | Ahn et al. (1996),<br>Moreno et al. (1997) |
| | 2000–2014 | x | x | x | | x | | x | | x | | Zhang et al. (2013),<br>Hale et al. (2008),<br>Poigner et al. (2013),<br>Vodopivez et al. (2015),<br>Negri et al. (2006),<br>Bargagli (2001), Majer et al. (2014), Bargagli (2008) |
| Fishes | Up to 1989 | x | | | x | x | | x | | | x | Subramanian et al. (1983),<br>Platt and Mackie (1980),<br>Aono et al. (1997) |
| | 1990–1999 | | | | | | | | | x | | Moreno et al. (1997) |
| | 2000–2014 | x | x | x | x | x | | x | | x | | Corsolini et al. (2002a, b),<br>Corsolini et al. (2006),<br>Corsolini (2009),<br>Hale et al. (2008),<br>Borghesi et al. (2009),<br>Borghesi et al. (2008), Weber and Goerke (2003), Lana et al. (2014),<br>Bargagli (2001),<br>Santos et al. (2006) |

(continued)

**Table 2** (continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seabirds | Up to 1989 | x | | | x | x | | | | x | | Sen Gupta et al. (1996), Risebrough et al. (1969), Aono et al. (1997), Luke et al. (1989), Bargagli (2008) |
| | 1990–1999 | x | x | x | | x | | | | | | Sen Gupta et al. (1996), Court et al. (1997), Aono et al. (1997), Inomata et al. (1996) |
| | 2000–2014 | x | x | x | x | x | x | x | | x | | Corsolini et al. (2006), Corsolini et al. (2011), Schiavone et al. (2009a), Geisz et al. (2008), Cipro et al. (2010), Yogui and Sericano (2009), Taniguchi et al. (2009), Van den Brink et al. (2011), Corsolini et al. (2007), Bustnes et al. (2006), Llorca et al. (2012), Van den Brink et al. (2011), Senthil et al. (2002), Tao et al. (2006), Taniguchi et al. (2009), Brasso and Polito (2013), Santos et al. (2006), Smichowski et al. (2006), Jerez et al. (2013a), Jerez et al. (2011), Bargagli (2001) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Marine mammals | Up to 1989 | x | | | x | x | | | | x | x | Schiavone et al. (2009a), Aono et al. (1997), Bargagli (2008), Risebrough and Carmlgnani (1972), McClurg (1984), Yamamoto et al. (1987) |
| | 1990–1999 | | | | x | | | | | x | | Aono et al. (1997), Schiavone et al. (2009a), Malcolm et al. (1994), Moreno et al. (1997), Aono et al. (1997), Szefer et al. (1993) |
| | 2000–2014 | x | x | x | x | x | x | | x | x | | Cipro et al. (2012), Schiavone et al. (2009c), Schiavone et al. (2009a), Corsolini et al. (2002a), Trumble et al. (2012), Krahn et al. (2007), Bengtson Nash et al. (2010), Senthil et al. (2002), Tao et al. (2006), Santos et al. (2006) |
| Alge | Up to 1989 | | | | | | | | | | | – |
| | 1990–1999 | | | | | | | | | x | | Moreno et al. (1997) |
| | 2000–2014 | x | | x | | x | | x | | x | | Cabrerizo et al. (2012), Runcie and Riddle (2004), Santos et al. (2006) |
| Antarctic lichens | Up to 1989 | | | | | | | | | | | – |
| | 1990–1999 | | | | | | | | | x | | Poblet et al. (1997), Olech et al. (1998), Upreti and Pandev (1994), Bargagli et al. (1999) |
| | 2000–2014 | x | x | x | | x | x | x | | x | | Cipro et al. (2011), Cabrerizo et al. (2012), Yogui and Sericano (2008), |

(continued)

**Table 2** (continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Yogui et al. (2011), Mão de Ferro et al. (2013), Osyczka et al. (2007), Santos et al. (2006) |
| Antarctic mosses | Up to 1989 | | | | | | | | | | | – |
| | 1990–1999 | **x** | **x** | **x** | | **x** | | | | **x** | | Focardi et al. (1991), Bargagli et al. (1995) |
| | 2000–2014 | **x** | **x** | **x** | | **x** | **x** | **x** | | **x** | | Yogui and Sericano (2008), Yogui et al. (2011), Borghini et al. (2005), Cipro et al. (2011), Cabrerizo et al. (2012), Mão de Ferro et al. (2013), Osyczka et al. (2007), Santos et al. (2006) |

[a] Heptachlor epoxide and nanochlors

[b] Sulphate, methyl Hg, n- alkanes, aliphatic hydrocarbons, chlorinated terphenyls, and TOC

[c] Mirex, dieldrin, endosulfan (I/II)

[d] PCNs, PCDDs, PCDFs; sulphate, methyl Hg, n- alkanes, aliphatic hydrocarbons, chlorinated terphenyls, TOC

Authors decided to summary the first three decades of analytical research as historic ones (up to the end of 1989). During this period only few data has been published, hence this period is three decades long. The period between 1990 and 1999 was relatively abundant in terms of applied analytical research, so it has been limited to only one decade. The last period contains years form 2000 up to present times. Authors do not see the need to separate the last decade (incomplete), so this period is 15 years long

**Table 3** Detailed literature data on results of analytical research on (a) main POPs; (b) remaining organic compounds; (c) heavy metals in various types of biotic and abiotic samples collected in Antarctica in three time periods

| Main POPs detected in biotic samples | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type of sample | Sample | Localization | Range or average concentrations (±standard deviation, if available) | | | | | | | |
| | | | DDTs$^a$ | PCBs$^b$ | HCHs$^c$ | HCB | PBDEs$^d$ | PAHs | Unit | Literature |
| Data reported in 80th years and earlier | | | | | | | | | | |
| Fish | **Antarctic fishes**; **whole body** (*Pagothenia borchgrevinki*, *Trematomus bernacchii*, *T. hansoni*, *T. Newnesi*. *T. Borchgrevinki*) | near Syowa Station | 0.03–1.9 | 0.08–0.77 | – | – | – | – | μg/g wet wt | Subramanian et al. (1983) |
| | **Antarctic code**; **flesh** (*Notothenia rossii*) | King Edward Cove | – | – | – | – | – | 0.01–0.5 | ng/g wet wt | Platt and Mackie (1980) |
| | **Antarctic code**; **liver** (*Notothenia rossii*) | | – | – | – | – | – | 0.01–0.11 | ng/g wet wt | |
| Seabirds | **Chinstrap penguin** (*Pygoscelis antarcticus*) | – | 0.63–4.27 | – | – | – | – | – | pg/g | Sen Gupta et al. (1996) |
| | **Macaroni penguin** (*Eudyptes chrysolophus*) | – | 500 | – | – | – | – | – | pg/g | |
| | **Migrating snow petrel** (*Pagodroma nivea*) | – | 600 | – | – | – | – | – | pg/g | |
| Marine mammals | **Crabeater seals** (*Lobodon carcinophagus*) | – | 7–17 | – | – | – | – | – | ng/g | Corsolini (2009) |
| Data reported from 1990 up to 1999 | | | | | | | | | | |
| Crustaceans | **Krill** (*Euphausia superba*) | Dakshin Gangotri, Queen Maud Land | 31.1–44.4 | 146.9–166.2 | 141.3–164.3 | – | – | – | pg/g dry wt | Sen Gupta et al. (1996) |
| | | – | 0.56 | <1.0 | 0.028 | 0.30 | – | – | ng/g wet wt | Aono et al. (1997) |
| Seabirds | **Penguin**; **feathers** | Dakshin Gangotri, Queen Maud Land | 30.8–35.7 | 105.8–113.6 | 103.6–112.8 | – | – | – | pg/g dry wt | Sen Gupta et al. (1996) |
| | **Adélie penguin**; **eggs** (*Pygoscelis adeliea*) | Cape Bird, Ross Island | 12.1–97.4 | 18.7–110.6 | – | 12.5–57.2 | – | – | ng/g dry wt | Court et al. (1997) |
| | **Adélie penguin**; **liver** (*Pygoscelis adeliea*) | | 24.3 ± 12.8 | 618.0 ± 506.0 | – | 15.9 ± 3.9 | – | – | | |
| | **South polar skuas**; **liver** (*Catharacta maccormicki*) | | 263.4 ± 209.2 | 2546.0 ± 1675.0 | – | 49.6 ± 26.0 | – | – | | |
| | **Gentoo penguin**; **fat tissue** (*Pygoscelis papua*)<br>**Adélie penguin**; **fat tissue** (*Pygoscelis adeliea*) | Admiralty Bay, King George Island | 30.8–972.3 | 43.2–1583.6 | <LOD$^e$–39.3 | 42.3–1159.7 | – | – | ng/g | Inomata et al. (1996) |

(continued)

**Table 3** (continued)

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|---|---|---|---|---|---|---|---|---|---|---|
| Marine mammals | **Minke whale**; **blubber** (*Balaenoptera Acutorostrata*) | – | 27–380 | 13–210 | 0.67–5.7 | 39–290 | – | – | ng/g wet wt | Aono et al. (1997) |
| Flora | **Antarctic mosses** | Kay Island, Ross Sea and Antarctic Peninsula | 0.2–0.5 | <5–16 | 0.2–1.7 | 0.3–0.8 | – | – | ng/g dry wt | Focardi et al. (1991) |
| Data reported from 2000 up to 2014 | | | | | | | | | | |
| Crustaceans | **Krill** (*Euphausia superba*) | Ross Sea | 0.22–2.30 | 85.27–282.29 | – | 0.2–0.6 | – | – | ng/g wet wt | Corsolini et al. (2002b) |
| | | | 0.07–0.10 | – | 0.28 ± 0.04 | 0.23 ± 0.01 | 0.17–0.23 | – | ng/g wet wt | Corsolini et al. (2006) |
| | | | – | – | 0.001–0.32 | 0.006–0.06 | – | – | ng/g wet wt | Cincinelli et al. (2009) |
| | | | – | 1.9 | – | – | – | – | ng/g wet wt | Corsolini et al. (2002a) |
| | | Admiralty Bay, King George Island | 0.05–0.79 | 4.66–13.6 | – | <LOD–0.06 | – | – | ng/g wet wt | Cipro et al. (2010) |
| Phytoplancton | – | Southern Ocean areas (Weddell, South Scotia, and Bellingshausen Seas) | – | 2.67 ± 0.86–14.07 ± 12.72 | 0.16 ± 0.17–1.81 ± 2.11 | 1.64 ± 2.4–4.34 ± 4.34 | – | – | ng/g dry wt | Galbán-Malagón et al. (2013b) |
| | – | Palmer Station | – | – | 0.45 ± 0.38–1.24 ± 1.65 | 2.9 ± 1.76 | – | – | ng/g lipid wt | Chiuchiolo et al. (2004) |
| Benthic organisms | **Antarctic invertebrates** (*Protelpidia murrayi*, *Peniagone vignoni*, *Bathyplotes natans*, *Molpadia musculus*) | Western Antarctic Peninsula | 0.26 ± 0.15 | 0.84–10.3 | 0.14–0.35 | 0.87 ± 0.34 | – | – | ng/g lipid wt | Zhang et al. (2013) |
| | **Antarctic invertebrates** *clams* (*Laternula elliptica*), *sea stars* (*Odontaster validus*), *sea urchins* (*Sterechinus neumayeri*), *sponges* (*Haliclona sp. and Homaxinella balfourensis*), *proboscis worms* (*Parborlasia corrugatus*) | Mc Murdo Sound | – | – | – | – | – | 356 ± 196 | ng/g lipid wt | Hale et al. (2008) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Fish | **Silverfish**; **larva** (*Pleurgramma antarcticum*) | Ross Sea | 1.51–2.03 | 497.81–509.88 | – | 0.88–4.04 | – | – | ng/g wet wt | Corsolini et al. (2002b) |
| | **Silverfish**; **adults** (*Pleurgramma antarcticum*) | | 0.04–5.70 | 16.2–1050.58 | – | 0.07–14.93 | – | – | | |
| | **Silverfish** (*Pleurgramma antarcticum*) | | – | 138 | – | – | – | – | ng/g wet wt | Corsolini et al. (2002a) |
| | **Rockcod**; **whole body** (*Trematomus bernacchii*) | | 0.02–2.53 | – | 0.03–0.17 | 1.35 ± 1.24 | 0.15– 0.16 | – | ng/g wet wt | Corsolini et al. (2006) |
| | **Rockcod**; **muscle** (*Trematomus bernacchii*) | | 0.11–1.1 | – | 0.03–1.23 | 1.44 ± 0.45 | 0.02–0.06 | – | | |
| | **Rockcod**; (*Trematomus bernacchii*) | | – | – | – | – | – | 1520–1840 | ng/g lipid wt | Hale et al. (2008) |
| | **Antarctic fish** (*Chionodraco hamatus*, *Chaempsocephalus gunnari*,*Gymnoscopelus nicholsi*, *Trematomus eulepidotes*) | | – | – | – | – | 0.001–0.13 | – | ng/g wet wt | Borghesi et al. (2009) |
| | **Crocodile icefish**; **muscle** (*Chionodraco hamatus*) | | – | 0.07–0.95 | – | – | (0.085–0.300) | – | ng/g wet wt; | Borghesi et al. (2008) |
| | **Crocodile icefish**; **liver** (*Chionodraco hamatus*) | | – | 0.75–3.30 | – | – | (0.001–0.320) | – | | |
| | **Emerald rockcod**; **muscle** (*Trematomus bernacchii*) | | – | (0.35–4.20) | – | – | (0.220–0.530) | – | | |
| | **Emerald rockcod**; **liver** (*Trematomus bernacchii*) | | – | (5.20–28) | – | – | (0.500–1.100) | – | | |
| | **Antarctic fish**; **liver** (*Gobionotothen gibberifrons*, *Champsocephalus gunnari*, *Chaenocephalus aceratus*) | Elephant Island, South Shetland Islands | 5–13 | 0.4–2 | – | 15–20 | – | – | ng/g lipid wt | Weber and Goerke (2003) |
| | **Sharp-spined notothen** (*Trematomus pennellii*) | Ross Sea | – | 111–175 | – | – | – | – | ng/g wet wt | Corsolini et al. (2002a) |
| | **Nototheniods fish**; **muscle** (*Trematomus newnesi*, *Notothenia coriiceps*, *Notothenia rossii*) | Potter Cove, King George Island | <LOD–7.31 | <LOQ[f]–8.33 | <LOQ–3.44 | – | <LOQ–8.53 | – | ng/g lipid wt | Lana et al. (2014) |
| | **Nototheniods fish**; **liver** (*Trematomus newnesi*, *Notothenia coriiceps*, *Notothenia rossii*) | | <LOD–10.5 | <LOQ–7.00 | <LOQ–0.99 | – | <LOQ–73.6 | – | ng/g lipid wt | Lana et al. (2014) |
| | **Nototheniods fish**; **gonads** (*Trematomus newnesi*, *Notothenia coriiceps*, *Notothenia rossii*) | | <LOQ–98.8 | <LOQ–46.9 | 2.41–24.2 | – | <LOQ–4.86 | – | ng/g lipid wt | Lana et al. (2014) |
| | **Nototheniods fish**; **gills** (*Trematomus newnesi*, *Notothenia coriiceps*, *Notothenia rossii*) | | <LOQ–43.0 | <LOQ–14.8 | 1.57–9.95 | – | <LOQ–39.8 | – | ng/g lipid wt | Lana et al. (2014) |

(continued)

## Table 3 (continued)

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|---|---|---|---|---|---|---|---|---|---|
| Seabirds | **Penguin adèlie**; **eggs** (*Pygoscelis adèliae*) | Ross Sea | 0.31–20.7 | – | 0.05–0.54 | 18.7 ± 8.0 | 0.03–0.65 | – | ng/g wet wt | Corsolini et al. (2006) |
| | | | <LOD–55.80 | 0.03–114.28 | – | 0.12–8.00 | – | – | ng/g wet wt | Corsolini et al. (2011) |
| | | Brainsfield Strait | <LOD–35.13 | 7.26–16.81 | 0.06–1.14 | 5.49–10.56 | – | – | ng/g wet wt | Corsolini et al. (2011) |
| | | King George Island, South Shetland | 23 ± 10 | 12 ± 4 | – | 7.63 ± 1.8 | – | – | ng/g wet wt | Schiavone et al. (2009a) |
| | | Palmer Archipelago | 58.5–755 | – | – | – | – | – | ng/g lipid wt | Geisz et al. (2008) |
| | **Penguin emperor**; **eggs** (*Aptenodytes forsteri*) | Ross Sea | 3.86–10.82 | 2.52–7.69 | – | <LOD–6.57 | – | – | ng/g wet wt | Corsolini et al. (2011) |
| | **Penguins**; **eggs** (**pooled together**)<br>**Penguins adèlie** (*Pygoscelis adèliae*)<br>**Gentoo penguin** (*Pygoscelis papua*)<br>**Chinstrap penguin** (*Pygoscelis antarcticus*) | Admiralty Bay King George Island | 2.07–38.0 | 2.53–78.7 | <LOD–6.19 | 4.99–39.1 | – | – | ng/g wet wt | Cipro et al. (2010) |
| | **Gentoo penguin**; **eggs** (*Pygoscelis papua*) | Antarctic Peninsula | – | – | – | – | – | 3.03–22.7 | ng/g lipid wt | Yogui and Sericano (2009) |
| | | King George Island, South Shetland | 15 ± 9 | 5 ± 3 | – | 3.7 ± 3.5 | – | – | ng/g wet wt | Schiavone et al. (2009a) |
| | **Chinstrap penguin**; **eggs** (*Pygoscelis antarcticus*) | Antarctic Peninsula | – | – | – | – | – | 3.13–33.0 | ng/g lipid wt | Yogui and Sericano (2009) |
| | | King George Island, South Shetland | 17 ± 15 | 6 ± 4 | – | 3.8 ± 3.7 | – | – | ng/g wet wt | Schiavone et al. (2009a) |
| | **Penguins**; **fat tissue** (**pooled together**)<br>**Penguins adèlie** (*Pygoscelis adèliae*)<br>**Gentoo penguin** (*Pygoscelis papua*)<br>**Chinstrap penguin** (*Pygoscelis antarcticus*) | King George Island, South Shetland | 193 ± 16 | 256 ± 125 | 12.3 ± 9.1 | 373 ± 177 | – | 1588 ± 654 | ng/g lipid wt | Taniguchi et al. (2009) |
| | **Penguin adèlie**; **fat** (*Pygoscelis adèliae* | Palmer Archipelago | 105–312 | – | – | – | – | – | ng/g lipid wt | Geisz et al. (2008) |
| | **Penguin adèlie**; **preen oil** (*Pygoscelis adèliae*) | Hop Island | – | 1–37 | – | 2–567 | – | – | ng/g lipid wt | Van den Brink et al. (2011) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Penguin adèlie**; **preen oil** (*Pygoscelis adèliae*) | Hop Island | – | 1–37 | – | 2–567 | – | – | ng/g lipid wt | Van den Brink et al. (2011) |
| | **Southern fulmar**; **preen oil** (*Fulmarus glacialoides*) | Hop Island | – | 1–40 | – | 1–314 | – | – | ng/g lipid wt | Van den Brink et al. (2011) |
| | **Penguin blood** (**pooled together**)<br>**Penguins adèlie** (*Pygoscelis adèliae*)<br>**Gentoo penguin** (*Pygoscelis papua*)<br>**Chinstrap penguin** (*Pygoscelis antarcticus* | Admiralty Bay, King George Island | 2.7–16 | 1.5–17 | – | 0.4–20 | 0.0017–1726 | – | ng/g wet wt | Corsolini et al. (2007) |
| | **Migrating snow petrel**; **eggs** (*Pagodroma nivea*) | Ross Sea | 3.64–10.83 | 15.23–22.66 | 0.03–0.37 | 10.43–15.40 | – | – | ng/g wet wt | Corsolini et al. (2011) |
| | **South polar skua**; **eggs** (*Catharacta maccormicki*) | Ross Sea | <LOD–64.75 | 1.69–64.23 | <LOD–0.080 | 9.23–43.39 | – | – | ng/g wet wt | Corsolini et al. (2011) |
| | | Antarctic Peninsula | – | – | – | – | 19.0–558 | – | ng/g lipid wt | Yogui and Sericano (2009) |
| | **South polar skua**; **blood** (*Catharacta maccormicki* | Dronning Maud Land | 0.4–40.9 | 1.0–50.5 | <0.1–6.5 | 0.6–21.2 | – | – | ng/g lipid wt | Bustnes et al. (2006) |
| | **Migrating brown skua**; **eggs** (*Catharacta antartica*) | Brainsfield Strait | 0.09–27.87 | 31.28–68.62 | <LOD–0.04 | 1.80–27.49 | – | – | ng/g wet wt | Corsolini et al. (2011) |
| | **Migrating brown skua**; **fat tissue** (*Catharacta antartica*) | King George Island, South Shetland | 6118 ± 3813 | 19,720 ± 9620 | 1.22–3.11 | 573 ± 278 | – | 3375 ± 1588 | ng/g lipid wt | Taniguchi et al. (2009) |
| | **Antarctic tern**; **fat tissue** (*Sterna vittata*) | King George Island, South Shetland | 524 ± 205 | 613 ± 187 | <0.12–2.60 | 601 ± 256 | – | 5744 ± 2546 | ng/g lipid wt | Taniguchi et al. (2009) |
| | **Blue-eyed shag**; **fat tissue** (*Phalacrocorax Atriceps*) | King George Island, South Shetland | 374 | 282 | 1.33 | 161 | – | 3961 | ng/g lipid wt | Taniguchi et al. (2009) |
| | **Snowy sheathbill**; **fat tissue** (*Chionis alba*) | King George Island, South Shetland | 468 | 297 | <0.12 | 282 | – | 4090 | ng/g lipid wt | Taniguchi et al. (2009) |

(continued)

**Table 3** (continued)

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|---|---|---|---|---|---|---|---|---|---|
| Marine mammals | **Southern elephant seal**; **liver** (*Mirounga leonina*) | King George Island, South Shetland | 460 | 150 | – | 2 | – | – | ng/g lipid wt | Cipro et al. (2012) |
| | **Antarctic fur seal**; **liver** (*Arctocephalus gazella*) | Livingston Island, Antarctic Peninsula | <2–2254 ± 3969 | 3 ± 0.8–429 ± 145 | 12 ± 20 | <2 | <0.04–10 ± 18 | – | ng/g lipid wt | Schiavone et al. (2009c) |
| | **Antarctic fur seal pup**; **liver** (*Arctocephalus gazella*) | Livingston Island, South Shetland | 191 ± 106 | 59 ± 43 | – | 2.2 ± 0.88 | – | – | ng/g wet wt | Schiavone et al. (2009a) |
| | **Antarctic fur seal pup**; **muscle** (*Arctocephalus gazella*) | | 103 ± 55 | 33 ± 22 | – | 1.37 ± 0.69 | – | – | | |
| | **Antarctic fur seal**; **fat tissue** (*Arctocephalus gazella*) | King George Island, South Shetland | 168 | 523 | 3.21 | 4.72 | – | – | ng/g lipid wt | Cipro et al. (2012) |
| | **Weddel seal**; **fat tissue** (*Leptonychotes weddelli*) | | 131 | 300 | 2.59 | 5.77 | 2.04 | – | | |
| | **Crabeater seal**; **fat tissue** (*Lobodon carcinophagus*) | | 14.4 | 154 | 0.223 | 7.23 | – | – | | |
| | **Weddel seal**; **blubber** (*Leptonychotes weddelli*) | Terra Nova Bay | 1.5–660 | 395 | – | – | – | | ng/g wet wt | Corsolini et al. (2002a) |
| | | McMurdo Sound | – | 0.52–18 | – | – | 1.2–1.8 | – | | Trumble et al. (2012) |
| | **Killer whales** (*Orcinus orca*) | Ross Sea | – | 1.6 ± 1.1 | – | – | – | – | μg/g lipid wt | Krahn et al. (2007) |

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|---|---|---|---|---|---|---|---|---|---|---|
| Flora | **Antarctic lichen** (*Usnea spp.*) | King George Island | 0.353 ± 0.04 | 7.76 ± 2.3 | 0.205 ± 0.08 | 0.141 ± 0.10 | 0.236 ± 0.05 | – | ng/g dry wt | Cipro et al. (2011) |
|  | **Antarctic lichens** (*Usnea Antarctica*) | Southern Shetlands | 0.003–0.01 | 0.043–0.61 |  | 0.002–0.31 | – | 15–40 | ng/g dry wt | Cabrerizo et al. (2012) |
|  | **Antarctic lichens** (*Usena aurantiaco-atra*) | Admirality Bay, King George Island, | – | – | – | – | 139 ± 33.6 | – | pg/g dry weight | Yogui and Sericano (2008) |
|  | **Antarctic lichens** (*Usnea aurantiaco-atra*) |  | – | – | – | – | 262 ± 48.7 | – |  | Yogui et al. (2011) |
|  | **Antarctic lichens** (*Usnea Antarctica*) |  | – | – | – | – | 192 ± 93.9 | – |  | Yogui and Sericano (2008) |
|  | **Antarctic lichens** (*Usnea aurantiaco-atra*) |  | – | – | – | – | 262 ± 48.7 | – |  | Yogui et al. (2011) |
|  | **Antarctic mosses** (*Sanionia uncinata*) |  | – | – | – | – | 818 ± 270 | – |  | Yogui and Sericano (2008) |
|  | **Antarctic mosses** (*Sanionia uncinata*) |  | – | – | – | – | 1022 ± 348 | – |  | Yogui et al. (2011) |
|  | **Antarctic mosses** (*Syntrichia princeps*) |  | – | – | – | – | 718 | – |  |  |
|  | **Antarctic mosses** (*Brachythecium sp.*) |  | – | – | – | – | 276 | – |  |  |
|  | **phanerogam** (*Colobanthus quitensis*) |  | – | – | – | – | 328 | – |  |  |
|  | **Antarctic mosses** (*Bryum argenteum*, *Pottia heimii*, *Ceratodon purpureus*) | Victoria Land | 0.54–7.9 | 23–34 | 0.18–4.0 | 0.82–1.95 | – | – | ng/g dry wt | Borghini et al. (2005) |
|  | **Antarctic mosses** (*Brachitecyum sp. Syntrichia princeps Sanionia uncinata*) | King George Island | <LOQ–1.73 | 7.76–18.6 | <LOQ–1.20 | 0.141–1.06 | 0.276–0.893 | – | ng/g dry wt | Cipro et al. (2011) |
|  | **Antarctic mosses** (*Sanionia uncinata.*) | Southern Shetlands | 0.005–0.04 | 0.04–0.76 | – | 0.21–0.12 | – | 4.4–34 | ng/g dry wt | Cabrerizo et al. (2012) |
|  | **Hair grass** (*Deschampsia antarctica*) | Southern Shetlands | 0.061–0.09 | 0.39–2.40 | – | 0.080–0.20 | – | 6–10 | ng/g dry wt | Cabrerizo et al. (2012) |
|  | **Pearl-wort** (*Colobanthus quitensis*) |  | 0.04 | 0.31 | – | 0.04 | – | 9.5 |  |  |
|  | **Green algae** (*Prasiola crispa*) |  | 0.08 | 0.86 | – | 0.033 | – | 7 |  |  |
|  | **Red snow algae** |  | 0.28 | 3.07 | – | 0.67 | – | 141 |  |  |
| Main POPs detected in abiotic samples |  |  |  |  |  |  |  |  |  |  |
| Type of sample |  | Localization | Range or average concentrations (±standard deviation, if available) |  |  |  |  |  |  |  |
|  |  |  | DDTs | PCBs | HCHs | HCB | PBDEs | PAHs | UNIT | LIT |
| Data reported in 80th years and earlier |  |  |  |  |  |  |  |  |  |  |
| Air |  | – | 150 | – | – | – | – | – | pg/m$^3$ | Sen Gupta et al. (1996) |
| Snow |  | East Antarctica | – | – | 2300–4900 | – | – | – | pg/L | Kang et al. (2012) |
|  |  | – | 0.63–4.27 | – | – | – | – | – |  | Sen Gupta et al. (1996) |

(continued)

**Table 3** (continued)

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|---|---|---|---|---|---|---|---|---|---|
| Fresh water | – | 1.3–30.7 | – | 1665 | – | – | – | pg/L | Sen Gupta et al. (1996) |
| Sediments | King Edward Cove | – | – | – | – | – | 2–220 | ng/g dry wt | Platt and Mackie (1980) |
| Data reported from 1990 up to 1999 | | | | | | | | | |
| Air | Ross Island | 1.0–2.0 | 12.2 | 25.8 | – | – | – | pg/m$^3$ | Larsson et al. (1992) |
| Air (ambient air) | Signy Island | 0.07–0.40 | 0.02–17 | 22 | – | – | – | pg/m$^3$ | Kallenborn et al. (1998) |
| Air (atmospheric particulates) | Terra Nova Bay | – | – | – | – | – | <1.5–689 | pg/m$^3$ | Caricchia et al. (1995) |
| Soil | McMurdo Sound—Dry Valley Region (fuel-oil contaminated area) | – | – | – | – | – | 46–3398 | ng/g dry weight | Aislabie et al. (1999) |
| | McMurdo Station | – | – | – | – | – | 28–27,000 | ppb | Mazzera et al. (1999) |
| | | – | – | – | – | – | 6267–6339 | ppm | Kennicutt et al. (1995) |
| | Victoria Land | – | 60 | – | – | – | – | pg/g dry wt | Fuoco et al. (1996) |
| Sediments | Ross Sea | – | 80 | – | – | – | – | pg/g dry wt | Fuoco et al. (1996) |
| | Winter Quarters Bay | – | 100–1400 | – | – | – | – | ng/g | Risebrough et al. (1990) |
| | Victoria Land | – | 120 | – | – | – | – | pg/g dry wt | Fuoco et al. (1996) |
| | – | 605.03–844.9 | – | 92.9–123.2 | – | – | – | pg/g | Sen Gupta et al. (1996) |
| Seawater | Admiralty Bay, King George Island | – | – | – | – | – | 0.003–0.011 | µg/L | Bicego et al. (1996) |
| Polynya water | Dakshin Gangotri | 24.8–26.5 | 96.8–103.8 | 85.6–90.7 | – | – | – | pg/L | Sen Gupta et al. (1996) |

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|---|---|---|---|---|---|---|---|---|---|
| Data reported from 2000 up to 2014 |  |  |  |  |  |  |  |  |  |
| Air (gase phase) | Western Ross Sea | – | – | 0.1–1.05 | 7.23–20.39 | – | – | pg/m$^3$ | Cincinelli et al. (2009) |
|  | Western Antarctic Peninsula | – | – | 0.06–2.98 | 11.9–32.1 | – | – |  | Dickhut et al. (2005) |
|  | Livingston Island (Antarctica) | – | 4–29 | – | – | – | – |  | Cabrerizo et al. (2013) |
|  | South Scotia Sea | – |  | 1.63 ± 1.52–1.70 ± 2.16 | 49.71 ± 8.19 | – | – |  | Galbán-Malagón et al. (2013a) |
|  | Weddell | – |  | 0.16 ± 0.14–0.87 ± 0.88 | 11.93 ± 15.77 | – | – |  |  |
|  | Livingston Island | – |  | 0.79 ± 0.77–2.27 ± 0.68 | 10.30 ± 4.81–11.97 ± 2.67 | – | – |  |  |
|  | Southern Ocean, Antarctic Peninsula | – | 1–70 | – | – | – | – |  | Galbán-Malagón et al. (2013c) |
|  | Terra Nova Bay | – | <LOD–0.25 | – | – | – | – |  | Gambaro et al. (2005) |
|  | Southern Ocean | – | – | – | – | – | 0.03–4.58 | ng/m$^3$ | Cabrerizo et al. (2014) |
| Air (aerosol phase) | Southern Ocean, Antarctic Peninsula | – | 0.04–0.4 | – | – | – | – | pg/m$^3$ | Galbán-Malagón et al. (2013c) |
| Air | King George Island | – | 1.66–6.5 | – | – | 0.67–2.98 | – | pg/m$^3$ | Li et al. (2012) |
|  |  | – | <LOD–117.8 | – | – | – | – |  | Choi et al. (2008) |
|  |  | – | <LOD–33.2 | – | – | – | – |  | Montone et al. (2003) |
|  |  | – | – | 2.5–3.65 | – | – | – |  | Baek et al. (2011) |
|  | Antarctic Ocean | <2.7–5.2 | <2.3–22.8 | <2.7–4.6 | 3.3–25.3 | – | – |  | Montone et al. (2005) |
|  | Dronning Maud Land | 0.02–0.20 | – | 0.02–0.46 | 22 | – | – |  | Kallenborn et al. (2013) |
| Snow | Dome Fuji, East Antarctica | – | – | 17.5–137.0 | <LOD–182 | – | – | pg/L | Kang et al. (2012) |
|  | Victoria Land | – | 110–580 | – | – | 130–340 | 0.65–140 | pg/L | Vecchiato et al. (2015) |
| Snow/firn core | Talos Dome | – | 0.03–0.24 | – | – | – | 0.35–4.6 | ng/L | Fuoco et al. (2012) |

(continued)

**Table 3** (continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Snow-ice cover | Russian Antarctic stations (*Molodezhnaya*, *Cosmonaut Sea*; *Progress*, *Prydz Bay*, *Commonwealth Sea*; *and Mirnyi*, *coastal part of the Davis Sea*) | – | – | – | – | – | <10 | ng/L | Nemirovskaya (2006) |
| Seawater | Western Ross Sea | – | – | 0.61–8.79 | 1.72–16.24 | – | – | pg/L | Cincinelli et al. (2009) |
| | Ross Sea | – | – | – | – | – | 1.21–3.96 | ng/L | Cincinelli et al. (2008) |
| | Ross Sea | – | 23–45 | – | – | – | 2–104 | pg/L | Fuoco et al. (2009b) |
| | Gerlache Inlet sea | – | – | – | – | – | 7.32–553 | ng/L | Stortini et al. (2009) |
| | **Southern Ocean areas** (**Weddell**, **South Scotia**, **and Bellingshausen Seas**) | – | 1.34 ± 0.398–3.727 ± 1.466 | 0.189 ± 0.09–3.132 ± 4.031 | 0.281 ± 0.078–0.976 ± 0.828 | – | – | pg/L | Galbán-Malagón et al. (2013b) |
| Porewater | Western Antarctic Peninsula | 0.11–1.00 | 0.06–3.4 | – | 0.63–6.7 | – | – | pg/L | Zhang et al. (2013) |
| Sediments | Western Antarctic Peninsula | – | 0.003–0.35 | – | – | – | – | ng/g dry wt | Zhang et al. (2013) |
| | James Ross Island | 0.19–1.15 | 0.32–0.83 | 0.14–0.76 | 0.95–4 | – | 1.4–205 | ng/g | Klánová et al. (2008) |
| | Admiralty Bay | – | <0.05–57 | – | – | – | – | ng/g dry wt | Montone et al. (2001) |
| | King George Island, Potter Cove | – | – | – | – | – | 28 ± 3–1908 ± 114 | ng/g dry wt | Curtosi et al. (2007) |
| | | – | – | – | – | – | 12.05–210.02 | ng/g | Dauner et al. (2014) |
| | McMurdo Sound | – | – | – | – | – | 38,326–5024 | ng/g | Kim et al. (2006) |
| | | – | 11–21 | – | – | – | 0.27–0.55 | ng/g | Negri et al. (2006) |
| | Winter Quarters Bay, Mc Murdo Station | – | <LOD–4299 | – | – | – | <LOD–12,848 | ng/g | Crockett and White (2003) |
| Sediment cores | Admiralty Bay, King George Island | – | – | – | – | – | 46.9–454.9 | ng/g | Martins et al. (2010) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Soil | Victoria Land | 0.053–0.086 | 0.36–0.59 | – | 0.034–0.17 | – | – | ng/g dry wt | Borghini et al. (2005) |
| | James Ross Island | 0.51–3.68 | 0.51–1.82 | 0.49–1.34 | 2.41–7.75 | – | 34.9–171 | ng/g | Klánová et al. (2008) |
| | Southern Shetlands | LOQ–0.20 | 0.005–0.15 | – | <LOQ–0.07 | – | 0.16–3718 | ng/g dry wt | Cabrerizo et al. (2012) |
| | East Antarctic coast | 0.11–1.22 | 0.20–0.41 | 0.86–4.69 | – | – | 12 ± 1–1182 ± 113 | ng/g dry wt | Negoita et al. (2003) |
| | | – | – | 0.09–40.1 | 0.02–25.28 | – | – | ng/g | Kang et al. (2012) |
| | Potter Cove, Jubany Station | – | – | – | – | – | 19–42 | ng/g dry wt | Curtosi et al. (2007) |

[a] DDTs: p,p’-DDE; o,p’-DDT; p,p’-DDD; p,p’-DDT

[b] PCBs: congeners (penta-CB: 99, 101, 105, 118; hexa-CB: 128, 138, 146, 149, 151, 153, 156; hepta-CB: 170, 171, 174, 177, 180, 183, 187; octa-CB: 194, 195, 199; nona-CB:206; deca-CB: 209)

[c] HCHs: α-HCH; β-HCH; γ-HCH

[d] PBDEs: BDE-47; BDE-99; BDE-100 and others congeners (nos: 28,153, 154, 183)

[e] LOD—limit of detection

[f] LOQ—limit of quantification

**Table 3b** Detailed literature data on results of analytical research on (a) main POPs; (b) remaining organic compounds; (c) heavy metals in various types of biotic and abiotic samples collected in Antarctica in three time periods

| Various chemical compounds identified in biotic samples | | | | | | |
|---|---|---|---|---|---|---|
| Type of sample | | Compound groups/ determined compounds | | Range or average concentrations (±standard deviation, if available) | Unit | Literature |
| Data reported in 80th years and earlier | | | | | | |
| Crustances | **Krill** (*Euphausia superba*) | Hydrocarbons | n-alkanes | 0.5 | µg/g wet wt | Platt and Mackie (1980) |
| Benthic organisms | **Bivalve** (*Yoldia eightsii*) | Hydrocarbons | n-alkanes | 0.4 | | |
| Fish | **Antarctic code**; **flesh** (*Notothenia rossii*) | Hydrocarbons | n-alkanes | 0.05 | | |
| | **Antarctic code**; **liver** (*Notothenia rossii*) | Hydrocarbons | n-alkanes | 1.9 | | |
| Marine mammals | **Crabeater seal**; **tissues** (*Lobodon carcinophagus*) | DLCs | PCDFs | 3.7–6.1 | pg/g lw | Schiavone et al. (2009c) |
| | **Minke whale**; **blubber** (*Balaenoptera Acutorostrata*) | OCP | CHLs[g] | 9.6–59 | ng/g wet wt | Aono et al. (1997) |
| Flora | **teristial plants** (*Tortula robusta*, *Rostkovia magellanica*, *Festuca contracta Poa flabellata*, *Acaena magellanica*) | Hydrocarbons | n-alkanes | 15.7–420.5 | µg/g wet wt | Platt and Mackie (1980) |
| Data reported from 1990 up to 1999 | | | | | | |
| Crustances | **Krill** (*Euphausia superba*) | OCP | CHLs | 68 | pg/g wt wt | Aono et al. (1997) |
| Marine mammals | **Minke whale**; **blubber** (*Balaenoptera Acutorostrata*) | OCP | CHLs | 18–75 | ng/g wet wt | Aono et al. (1997) |
| | **Antarctic fur seal**; **tissues** (*Arctocephalus gazella*) | Dioxins | PCDDs | 15.7 | pg/g wet wt | Schiavone et al. (2009c) |
| | | DLCs | PCDFs | 7 | | |
| Data reported from 2000 up to 2014 | | | | | | |
| Crustances | **Krill** (*Euphausia superba*) | OCP | Chlordanes[h] | <LOD–0.13 | ng/g wet wt | (Cipro et al. (2010) |
| | | | Drins[i] | <LOD–0.54 | | |
| | | Dioxin | total PCDD/DFs | 27 | pg/g | Senthil et al. (2002) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Fish | **Antarctic fishes**; **muscle** (*Chionodraco Hamatus*, *Trematomus Bernacchii*) | Dioxins | PCDDs | 2.69–5.8 | pg/g wet wt | Borghesi et al. (2008) |
| | | DLCs | PCDFs | 1.53–1.68 | | |
| | **Antarctic fishes**; **liver** (*Chionodraco Hamatus*, *Trematomus Bernacchii*) | Dioxins | PCDDs | 4.6–4.94 | | |
| | | DLCs | PCDFs | 1.25–2.3 | | |
| | **Antarctic fishes**; (*Trematomus pennelli*, *Chionodrodraco hamatus*) | Dioxin | Total PCDD/DFs | 11–17 | pg/g | Senthil et al. (2002) |
| | **Emerald rockcod**; (*Trematomus bernacchii*) | OCP | CHLs | 2.61 ± 2.07 | ng/g wet wt | Corsolini (2009) |
| | **Antarctic fishes**; **liver** (*Champsocephalus gunnari*, *Gobiontothen gibberifrons*, *Chanocephelus aceratus*) | OCP | Mirex | 1–7 | ng/g lipid wt | Weber and Goerke (2003) |
| Seabirds | **Pinguin**; **dung** (*Pygoscelis papua*) | Surfactants | PFCs[j] | 0.63–603 | ng/g | Llorca et al. (2012) |
| | **Pinguin**; **muscle tissues** (*Pygoscelis papua*) | Surfactants | PFCs | <LOQ[f]–2.28 | ng/g | Llorca et al. (2012) |
| | **Penguin**; **preen oil** (*Pygoscelis adeliae*) | OCP | Dieldrin | 2–24 | ng/g lipid wt | Van den Brink et al. (2011) |
| | **Penguins**; **fat tissue** (*Pygoscelis adeliae*, *Pygoscelis papua*, *Pygoscelis antarctica*) | OCP | Dieldrin | 47.1 ± 12.4 | ng/g lipid wt | Cipro et al. (2012); Cipro et al. (2010); Corsolini et al. (2007); Senthil et al. (2002), Tao et al. (2006); Taniguchi et al. (2009) |
| | | | Mirex | 26.4 ± 20.2 | | |
| | | | Dieldrin | 26.4 ± 19.1 | | |
| | | | Mirex | 90.6 ± 70.6 | | |
| | **Penguin**; **blood** (*Pygoscelis adeliae*) | Surfactants | PFOS | <0.1 | ng/ml | |
| | **Penguin**; **blood** (*Pygoscelis adeliae*, *Pygoscelis papua Pygoscelis antarctica*) | Dioxins | PCDDs | 0.7–103 | pg/g wet wt | |
| | | DLCs | PCDFs | 0.8–194 | | |

(continued)

**Table 3b** (continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| | **Penguin**; **eggs** (*Pygoscelis adeliae*, *Pygoscelis papua Pygoscelis antarctica*) | Surfactants | PFOS | <0.1–8.8 | ng/g | |
| | | OCP | Chlordanes | 0.32–7.57 | ng/g wet wt | |
| | | | Mirex | 0.67–6.37 | | |
| | | | Drins | 0.06–35.8 | | |
| | **Penguin**; **eggs** (*Pygoscelis adeliae*) | Dioxins | eoni PCDD/DFs | 23 | pg/g | |
| | **South polar skua**; **blood** (*Catharacta maccormicki*) | Surfactants | PFOS | <0.24–1.36 | ng/ml | |
| | **South polar skua**; **egg** (*Catharacta maccormicki*) | Surfactants | PFOS | 2.08–3.12 | ng/g | |
| | **Brown skua**; **fat tissue** (*Catharacta Antarctica*) | OCP | Chlordanes | 977 ± 445 | ng/g lipid wt | |
| | | | Oxychlordane | 408 ± 169 | | |
| | | | Dieldrin | 254 ± 158 | | |
| | | | Mirex | 2210 ± 1590 | | |
| | **Antarctic tern**; **fat tissue** (*Sterna vittata*) | OC | Chlordanes | 80.6 ± 47.1 | | |
| | | | Oxychlordane | 44.2 ± 21.0 | | |
| | | | Dieldrin | <0.48–23.0 | | |
| | | | Mirex | 260 ± 58 | | |
| | **Blue-eyed shag**; **fat tissue** (*Phalacrocorax Atriceps*) | OCP | Chlordanes | 3.05 | | |
| | | | Oxychlordane | <0.24 | | |
| | | | Dieldrin | <0.48 | | |
| | | | Mirex | 89.2 | | |
| | **Snowy sheathbill**; **fat tissue** (*Chionis alba*) | OCP | Chlordanes | 468 | | |
| | | | Oxychlordane | 63.3 | | |
| | | | Dieldrin | 22.4 | | |
| | | | Mirex | 149 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **Whitechinned petrel**; **pectoral muscle** (*Procellaria aequioctialis*) | surfactants | PFOS | 1.2–2.0 | ng/g | Llorca et al. (2012) |
| | **Southern fulmar**; **preen oil** (*Fulmarus glacialoides*) | OCP | Dieldrin | 1–38 | ng/g lipid wt | Van den Brink et al. (2011) |
| Marine mammals | **Seals**; **tissues** (**muscle**, **blubber**, **fur**) | OCP | Drins | 18.4–82.4 | ng/g lipid wt | Cipro et al. (2012); Bengtson Nash et al. (2010); Schiavone et al. (2009a, c); Corsolini et al. (2002b) |
| | **Antarctic fur seal** (*Arctocephalus gazella*) | | Endosulfan (I/II) | 2.09–21.15 | | |
| | **Other seal spiecies** (*Leptonychotes weddelli*, *Lobodon carcinophagus*) | | Mirex | 5.53–17.0 | | |
| | | | Chlordanes | 9.5–78.2 | | |
| | | – | PCNs | 0.01–3.08 | | |
| | | Dioxins | PCDDs | 3.5–53.6 | ng/g wet wt | |
| | | DLCs | PCDFs | 8.5–96.4 | | |
| | | Surfactants | PFCs | <0.4–2.0 | ng/g | |
| | **Seals**; **liver** | Pesticides OCP | Drins | 6.88 | ng/g lipid wt | |
| | **Southern elephant seal** (*Mirounga leonine*) | | Endosulfan (I/II) | 2.72 | | |
| | **Antarctic fur seal** (*Arctocephalus gazella*) | | Mirex | 16.2 | | |
| | | | Chlordanes | 37.7 | | |
| | | Dioxins | PCDDs | 10.6 | ng/g wet wt | |
| | | DLCs | PCDFs | 153.7 | | |
| | | Surfactants | PFCs | <0.4–12.6 | ng/g | |
| | **Weddell seal**; **liver** (*Leptonichotes weddelli*) | Dioxin | total PCDD/DFs | 8.9 | pg/g | Senthil et al. (2002) |
| | **Southern elephant seal**; **blood** (*Mirounga leonine*) | PFCs | PFOS | <0.08–3.52 | ng/ml | Tao et al. (2006) |

(continued)

**Table 3b** (continued)

| Various chemical compounds identified in abiotic samples | | | | | |
|---|---|---|---|---|---|
| Type of sample | Compound groups/determined compounds | | Range or average concentrations (± standard deviation, if available) | Unit | Literature |
| Data reported in 80th years and earlier | | | | | |
| Snow | – | Sulphate | 50–100 | ng/g | Delmas and Boutron (1978) |
| Soil | Hydrocarbons | n-alkanes | 0.6 | μg/g | Platt and Mackie (1980) |
| Freshwater sediments | Hydrocarbons | n-alkanes | 0.9–1.7 | | |
| Seawater | Hydrocarbons | n-alkanes | 5.8 | | |
| Data reported from 1990 up to 1999 | | | | | |
| Air | OCP | Heptachlor epoxide | 0.52 | $pg/m^3$ | Bidleman et al. (1993); Kallenborn et al. (1998) |
| | | Chlordanes + nanochlors | 1.8 | | |
| | | Chlordanes | 0.04–0.9 | | |
| Seawater | Hydrocarbons | n-alkanes | 2.6–7.6 | μg/L | Guerra et al. (2013) |
| | | n-alkanes | 353–968 | ng/L | Stortini et al. (2009) |
| | | n-alkanes | 2.6–7.6 | μg/L | Cripps (1992) |
| Seawater (particulate matter) | Hydrocarbons | Aliphatic hydrocarbons | 0.07–0.17 | μg/L | Green et al. (1992) |
| Marine sediment | OC | Chlorinated terphenyls | 30–1200 | ng/g | Risebrough et al. (1990) |
| | Hydrocarbons | Aliphatic hydrocarbons | 45–48 | μg/g | Green et al. (1992) |
| | Organic carbon | TOC | 0.34 | g % | Vandal et al. (1998) |
| Sea ice | Hydrocarbons | Aliphatic hydrocarbons | 1.9–12.5 | $mg/m^2$ | Green et al. (1992) |

| | | | | | |
|---|---|---|---|---|---|
| Data reported from 2000 up to 2014 | | | | | |
| Air (gase phase) | Pesticides | Heptachlor | <1–19.1 | pg/m$^3$ | Dickhut et al. (2005) |
| | | Heptachlor epoxide | <0.3–20.7 | | |
| Air | – | Chlorinated paraffin | 3.7–20.8 | pg/m$^3$ | Ma et al. (2014) |
| | Pesticides | Aldrin and dieldrin | 12.2–88.5 | pg/m$^3$ | Baek et al. (2011) |
| | Hydrocarbons | Akryl nitrates | <LOD–1.11 | ppt(v) | Fischer et al. (2002) |
| Snow | Organic carbon | TOC | 88–928 | μg/L | Antony et al. (2011) |
| | Surfactants | PFCs | 1129.2–2491.3 | pg/L | Cai et al. (2012) |
| | Hydrocarbons | Chlorinated hydrocarbons | <LOD–380 | μg/g | Zoccolillo et al. (2007) |
| Fresh water | Surfactants | PFCs | 2121.8–5767.9 | pg/L | Cai et al. (2012) |
| Surface water | Surfactants | PFCs | <3.0–51 | pg/L | Ahrens et al. (2010) |
| Seawater | Surfactants | PFCs | 531.9–15,284 | pg/L | Cai et al. (2012) |
| Sediments | Hydrocarbons | n-alkanes | 0.03–0.41 | μg/g | Dauner et al. (2014) |
| Marine sediments | Hydrocarbons | n-alkanes | 1.1–2.1 | μg/g | Negri et al. (2006) |
| | | Total hydrocarbons | 81–144 | | |

[a] CHLs: oxychlordane + cis-chlordane + trans-nonachlor + cis – nonachlor

[b] Chlordanes: heptachlor + epoxides + oxychlordane + α-and β-chlordane

[c] LOD—limit of detection

[d] Drins: aldrin + endrin + dieldrin + isodrin

[e] PFCs: PFHxA, PFOA, PFNA, PFBS, PFOS

[f] LOQ—limit of quantification

**Table 3c** Detailed literature data on results of analytical research on (a) main POPs; (b) remaining organic compounds; (c) heavy metals in various types of biotic and abiotic samples collected in Antarctica in three time periods

| Heavy metals in biotic samples | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of sample | Sample | Localization | Range or average concentrations (±standard deviation, if available) | | | | | | | | | | Unit | Literature |
| | | | Fe | Cd | Co | Cr | Cu | Hg | Mn | Ni | Pb | Zn | | |
| Data reported in 80th years and earlier | | | | | | | | | | | | | | |
| Crustaceans | **Krill** (*Euphausia superba*) | Antarctic Scotia Sea | – | 0.85 | – | – | – | <0.1 | – | – | – | – | µg/g dry wt | Bargagli (2008) |
| | **Others** (*T. gaudichaudii*) | – | – | 18.7–52.6 | 28.1–31.1 | – | – | – | – | – | – | – | µg/g dry wt | Moreno et al. (1997) |
| Seabirds | **Penguin**; **liver** (*Pygoscelis adeliae*) | Southern Ocean | – | 13.0 | – | – | – | 0.2 | – | – | – | – | µg/g dry wt | Bargagli (2008) |
| Marine mammals | **Seal**; **liver** (*Ommatophoca rossi*) | | – | 110 ± 88 | – | – | – | 4.6 ± 4.3 | – | – | – | – | | |
| | **Whale**; **liver** (*Balaenoptera acutorosyrata*) | | – | 45 ± 26 | – | – | – | 0.21 ± 0.1 | – | – | – | – | | |
| Data reported from 1990 up to 1999 | | | | | | | | | | | | | | |
| Crustaceans | **Krill** (*Euphausia superba*) | Southern Ocean | – | 0.29 | – | – | – | 0.025 | – | – | – | – | µg/g dry wt | Bargagli (2008) |
| | **Other** (*Glyptonotus antarcticus Waldeckia obese*) | Antarctic Ocean | – | 0.98–1.89 | – | – | 72.80–165.0 | – | – | – | – | 60.60–335.0 | µg/g dry wt | Petri and Zauke (1993) |
| Benthic organisms | **Bivalve**; **digestive glands** (*Laternula elliptica*) | King George Island | 2003 | 11.5 | 2.84 | 2.9 | 38.1 | – | 18.6 | 6.27 | 5.49 | 153 | µg/g dry wt | Ahn et al. (1996) |
| | **Bivalve**; **gonad** (*Laternula elliptica*) | | 1832 | 4.75 | 1.48 | 1.7 | 15.0 | – | 30.1 | 4.47 | 2.15 | 84.9 | | |
| | **Bivalve**; **girls** (*Laternula elliptica*) | | 1998 | 7.21 | 2.71 | 2.9 | 21.4 | – | 44.7 | 6.16 | 2.77 | 206 | | |
| | **Bivalve**; **kidney** (*Laternula elliptica*) | | 4318 | 41.9 | 5.74 | 4.7 | 33.3 | – | 190 | 21 | 37.7 | 1687 | | |
| | **Bivalve**; **muscle** (*Laternula elliptica*) | | 800 | 3.9 | 2.28 | 1.69 | 50 | – | 102 | 2.74 | 1.35 | 115 | | |
| | **Invertebrates** (*Parborlasia corrugatus Anthozoa Nacella concinna Trophon, Waldeckia obesa Glyptonotus antarcticus Odontaster validus Neomilaster georgianus Sterechinus*) | Antarctic Paninsula | – | 0.20–15.60 | – | – | 0.3–49.70 | – | – | – | – | 4.23–46.12 | µg/g wet wt | Moreno et al. (1997) |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fish | **Notothenia; muscle** (*Notothenia coriceps*) | Antarctic Peninsula | – | <0.05 | – | – | 0.04–0.5 | 0.01–0.10 | – | – | – | 1.00–6.70 | µg/g wet wt | Moreno et al. (1997) |
| Marine mammals | **Antarctic fur seal; liver** (*Arctocephalus gazella*) | Bird Island, South Georgia; Sub-Antarctic | 0.1 | 350 | – | 1 | 263 | 215 | – | – | – | 384 | ng/g dry wt | Malcolm et al. (1994) |
| | | Antarctic Peninsula | – | 1.90–3.50 | – | – | 11.90–16.20 | 4.10–7.60 | – | – | – | 25.30–38.40 | µg/g wet wt | Moreno et al. (1997) |
| | **Antarctic fur seal; muscle** (*Arctocephalus gazella*) | Antarctic Peninsul | – | <0.05 | 1.10–1.50 | – | – | <0.05 | – | – | – | 12.70–25.70 | µg/g wet wt | Moreno et al. (1997) |
| | **Antarctic fur seal; kidnay** (*Arctocephalus gazella*) | | – | 3.70–5.90 | 8.40–22.30 | – | – | 0.20–0.30 | – | – | – | 23.80–38.90 | | |
| | **Antarctic fur seal; fat** (*Arctocephalus gazella*) | | – | <0.05 | 0.20–0.60 | – | – | <0.05 | – | – | – | 3.20–8.40 | | |
| | **Crabeater seal; muscle** (*Lobodon carcinophagus*) | | – | – | – | – | – | 0.27–6.2 | – | – | – | – | µg/g dry weight | Szefer et al. (1993) |
| | **Crabeater seal; liver** (*Lobodon carcinophagus*) | | – | – | – | – | – | 1.7–16.3 | – | – | – | – | | |
| | **Crabeater seal; kidney** (*Lobodon carcinophagus*) | | – | – | – | – | – | 1.7–2.5 | – | – | – | – | | |
| | **Leopard seal; muscle** (*Hydrurga leptonyx*) | | – | – | – | – | – | 1.06–3.22 | – | – | – | – | | |
| | **Leopard seal; liver** (*Hydrurga leptonyx*) | | – | – | – | – | – | 8.78–18.1 | – | – | – | – | | |
| | **Leopard seal; kidney** (*Hydrurga leptonyx*) | | – | – | – | – | – | 4.64–6.05 | – | – | – | – | | |
| | **Weddell seal; muscle** (*Leptonychotes weddelii*) | | – | – | – | – | – | 1.18–3.61 | – | – | – | – | | |
| | **Weddell seal; liver** (*Leptonychotes weddelii*) | | – | – | – | – | – | 21.1–48.8 | – | – | – | – | | |
| | **Weddell seal; kidney** (*Leptonychotes weddelii*) | | – | – | – | – | – | 9.67–15.9 | – | – | – | – | | |
| | **Southern elephant seal; muscle** (*Mirounga leonine*) | | – | 0.05–0.12 | – | – | 0.57–0.68 | 0.17–0.19 | – | – | – | 24.37–28.58 | µg/g wet wt | Moreno et al. (1997) |
| | **Southern elephant seal; skin** (*Mirounga leonine*) | | – | <0.05 | – | – | 0.49–0.52 | 0.09–0.14 | – | – | – | 25.07–30.72 | | |
| | **Southern elephant seal; fat** (*Mirounga leonine*) | | – | <0.05 | – | – | 0.54–1.46 | <0.05 | – | – | – | 0.30–0.84 | | |
| | **Minke whale; blubber** (*Balaenoptera Acutorostrata*) | – | 262.88–2050 | 0.03–0.28 | – | 1.4–8.9 | 1.63–93 | 0.08–0.43 | 6.77–443 | 0.7–9.5 | 0.6–19.8 | 3.64–104 | ng/g wet wt | Aono et al. (1997) |

(continued)

**Table 3c** (continued)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flora | **Algae** (*Desmarestia sp.*, *Durvillea Antarctica*, *Adenocystis sp.*, *Ascoseyra sp.*, *Cytosphaera sp.*, *Iridaea sp.*, *Leptosomia simplex st.*) | Antarctic Peninsula | – | 0.05–2.02 | – | – | 0.10–4.32 | – | – | – | – | 2.12–27.31 | µg/g dry wt | Moreno et al. (1997) |
| | **Antarctic mosses** (*B. argentatum*, *B pseudotriquwtrum*, *Ceratodon purpureus Pottia heimii*) | Edmonson Point | – | 0.10–0.92 | – | – | – | 0.05–0.15 | – | – | 0.3–1.4 | – | µg/g dry wt | Bargagli et al. (1995) |
| | **Antarctic lichens** (*Usena auranticoatra*) | King George Island | 262.88–1364.8 | <LOD[a]–0.015 | – | – | 1.63–5.79 | – | 6.77–39.16 | – | <LOD–2.76 | 3.64–17.92 | µg/g dry wt | Poblet et al. (1997) |
| | | | – | – | – | – | – | – | – | – | 3–39 | – | ppm | Olech et al. (1998) |
| | **Antarctic lichens** (*Usena antarctica*) | King George Island | 283.37–1115.1 | <LOD–0.03 | – | – | 2.17–9.49 | – | 15.65–56.03 | – | <LOD–2.85 | 5.52–21.43 | µg/g dry wt | Poblet et al. (1997) |
| | | | – | – | – | – | – | – | – | – | 4–160 | – | ppm | Olech et al. (1998) |
| | **Antarctic lichens** (*Usena decussata*) | Trishvil Hill base, East Antarctica | 4966–12,760 | – | – | 4.2–3.36 | 45–93 | – | – | – | 5.66–19.8 | – | µg/g dry wt | Upreti Pandev (1995) |
| | | Victoria Land | 802 ± 402 | 0.21 ± 0.11 | – | 1.3 ± 0.6 | 5.3 ± 5.1 | – | 11.8 ± 3.9 | – | 0.54 ± 0.34 | 18.6 ± 4.1 | µg/g dry wt | Bargagli et al. (1999) |
| Data reported from 2000 up to 2014 | | | | | | | | | | | | | |
| Zooplankton | **Whole body amphipoda** (*Paramoera orrug*) | Windmill Island | – | 7.2 ± 2.7 | – | – | – | 0.07 ± 0.03 | – | – | – | – | µg/g dry wt | Bargagli (2008) |
| | **Whole pooled across species** | Windmill Island | – | 3.4 ± 2.3 | – | – | – | 0.07 ± 0.03 | – | – | – | – | | |
| Crustaceans | **Krill** (*Euphausia superba*) | Admiralty Bay | 72 | – | – | – | – | 34.6* | – | – | – | 50.2 | µg/g; *ng/g | Santos et al. (2006) |
| | **Pooled across species** (*Bovallia gigantea* *Cheirimedon femoratus* *Gondogeneia antarctica*) | | 388–1108 | – | – | – | – | 35.0–37.0 | – | – | – | 62.1–84.1 | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benthic organisms | **Porifera; whole pooled across species** | Windmill Island | – | 26.4 ± 14.8 | – | – | – | 0.08 ± 0.05 | – | – | – | – | µg/g dry wt | Bargagli (2008) |
| | **Molluscs** (*Nacella conccina*) | Admirality Bay | 2756 | – | – | – | – | 26.1* | – | – | – | 64.4 | µg/g; *ng/g | Santos et al. (2006) |
| | **Bivalve; tissue** (*Laternula elliptica*) | McMurdo Sound | – | 5–57 | – | – | 4.2–543 | 0.1–21 | – | – | 0.3–6.4 | 48–419 | µg/g dry wt | Negri et al. (2006) |
| | **Bivalve; hemolymph** (*Laternula elliptica*) | King George Island | 5.6–458 | – | – | – | – | – | 0.1–4.0 | – | – | – | mmol/l | Poigner et al. (2013) |
| | **Bivalve; digestive gland** (*Laternula elliptica*) | King George Island | 981–2000 | – | – | – | – | – | 3.3–18.6 | – | – | – | µg/g dry wt | Poigner et al. (2013) |
| | | Potter Cove | 541–1413 | 6–22 | – | 0.5–9.4 | 52–108 | – | 4.6–15.1 | – | 0.4–2.5 | 105–133 | µg/g dry wt | Vodopivez et al. (2015) |
| | **Bivalve; gill** (*Laternula elliptica*) | King George Island | 350–2060 | – | – | – | – | – | 4.2–44.7 | – | – | – | µg/g dry wt | Poigner et al. (2013) |
| | | Potter Cove | 600–3150 | 1.5–5.1 | – | 0.5–2.3 | 6.2–31.8 | – | 9–67 | – | 0.19–1.16 | 84–139 | µg/g dry wt | Vodopivez et al. (2015) |
| | **Bivalve; mantle tissue** (*Laternula elliptica*) | King George Island | 119–9200 | – | – | – | – | – | 1.42–700 | – | – | – | µg/g dry wt | Poigner et al. (2013) |
| | **Bivalve; kidney** (*Laternula elliptica*) | Potter Cove | 900–1000 | 88–183 | | 0.5–2.8 | 21.5 | | 106–410 | | 29–489 | 1300–4500 | µg/g dry wt | Vodopivez et al. (2015) |
| | **Bivalve; digestive gland** (*Adamussium colbecki*) | Terra Nova Bay | – | 55.7 ± 27 | – | – | – | 0.35 ± 0.08 | – | – | – | – | µg/g dry wt | Bargagli (2001) |
| | **Bivalve; digestive gland** (*Neobuccinum eatoni*) | | – | 227 ± 65 | – | – | – | 0.24 ± 0.1 | – | – | – | – | | |
| | **Sponge tissue** (*Homaxinella balfourensis*, *Mycale acerata*, *Sphaerotylus antarcticus*) | McMurdo Sound | – | 7.8–57 | – | – | 2.3–25.3 | – | – | – | <0.2–22.4 | 16–135 | µg/g dry wet | Negri et al. (2006) |
| | **Whole tissue** (*Himantothallus grandifolius Gondogeneia orrugates Sterechinus neumayeri Nacella concinna Amphioplus acutus Paraserolis polita Bovalia gigantean*, *Parborlasia orrugates*) | Admiralty Bay, King George Island, | – | 0.25–21.5 | – | – | 1.0–119.12 | – | – | 0.37–8.28 | <0.6–9.31 | 2.5–353.91 | µg/g dry wt | Majer et al. (2014) |

(continued)

## Table 3c (continued)

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Whole holothuroidea pooled across species** | Windmill Island | – | 7.7 ± 3.8 | – | – | – | 0.23 ± 0.09 | – | – | – | – | µg/g dry wt | Bargagli (2008) |
| | **Asteroidean**; **arms** (*Odontaster validus*) | | – | 13.6 ± 1.8 | – | – | – | 0.11 ± 0.06 | – | – | – | – | | |
| | **Echinoidea**; **soft tissued** (*Sterechinus neumayeri*) | | – | 13.0 ± 4.8 | – | – | – | 0.1 ± 0.06 | – | – | – | – | | |
| | **Whole Polychaeta** (*Harmothor spinosa*) | | – | 6.8 ± 0.6 | – | – | – | 0.07 ± 0.02 | – | – | – | – | | |
| Fish | **Emerald rock cod**; **muscle** (*Trematomus Bernacchii*) | Terra Nova Bay | – | 0.04 ± 0.02 | – | – | – | 0.83 ± 0.65 | – | – | – | – | µg/g dry wet | Bargagli (2001) |
| | **Crocodile icefish**; **muscle** (*Chionodraco Hamatus*) | | – | 0.03 ± 0.02 | – | – | – | 0.44 ± 0.31 | – | – | – | – | | |
| | **Emerald rock cod**; **liver** (*Trematomus Bernacchii*) | | – | 9.9 ± 5.8 | – | – | – | 0.46 ± 0.25 | – | – | – | – | | |
| | **Crocodile icefish**; **liver** (*Chionodraco Hamatus*) | | – | 2.9 ± 0.8 | – | – | – | 0.19 ± 0.12 | – | – | – | – | | |
| | **Myctophid fish**; **liver** (*Gymnoscopelus piabilis*) | | – | 28 ± 17 | – | – | – | – | – | – | – | – | | |
| | **Myctophid fish**; **kidney** (*Gymnoscopelus piabilis*) | | – | 16 ± 8 | – | – | – | – | – | – | – | – | | |
| | **Myctophid fish**; **muscle** (*Gymnoscopelus piabilis*) | | – | <0.1 | – | – | – | 0.31 ± 0.13 | – | – | – | – | | |
| | **dusky rockcod** (*Trematomus newnesi*) | Admiralty Bay | 24 | – | – | – | – | 16.0* | – | – | – | 99.1 | µg/g; *ng/g | Santos et al. (2006) |
| | **Fish** (*Notothenia spp.*) | | 78 | – | – | – | – | 16.3* | – | – | – | 64.6 | | |
| Seabirds | **Penguin Adèlie** (*Pygoscelis adeliae*) | King George Island | – | – | – | – | – | 0.11 ± – 0.22 | – | – | – | – | ppm | Brasso and Polito (2013) |
| | | Ross Sea | – | – | – | – | – | 0.53 ± 0.08 | – | – | – | – | | |
| | **Penguin Adèlie**; **eggs** (*Pygoscelis adeliae*) | Admiralty Bay | – | – | – | – | – | 5.0* | – | – | – | 8.3 | µg/g; *ng/g | Santos et al. (2006) |
| | **Penguin Adèlie**; **kidney** (*Pygoscelis adeliae*) | Potter Cove, King George Island | – | 339 ± 12* | 143 ± 5* | – | 1.6 ± 0.12 | 146 ± 4* | 9.4 ± 0.2 | – | 144 ± 7* | – | µg/g; *ng/g dry wt | Smichowski et al. (2006) |
| | | South Shetland Islands | 327.03 ± 112.89 | 0.20 ± 0.15 | – | 0.21 ± 0.13 | 11.85 ± 3.69 | – | 11.18 ± 6.12 | 0.01 ± 0.0 | 0.05 ± 0.12 | 85.74 ± 19.49 | µg/g dry wt | Jerez et al. (2013a) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Penguin Adèlie**; **liver** (*Pygoscelis adeliae*) | Potter Cove, King George Island | – | 102 ± 7* | 68 ± 6* | – | 18 ± 1 | 269 ± 10* | 10.0 ± 0.2 | – | 202 ± 9* | – | μg/g; *ng/g dry wt | Smichowski et al. (2006) |
| | | South Shetland Islands | 1364.01 ± 351.09 | 0.06 ± 0.05 | – | 0.12 ± 0.06 | 92.06 ± 74.53 | – | 12.01 ± 5.80 | 0.01 ± 0.01 | 0.04 ± 0.07 | 133.88 ± 71.42 | μg/g dry wt | Jerez et al. (2013a) |
| | **Penguin Adèlie**; **muscle** (*Pygoscelis adeliae*) | Potter Cove, King George Island | – | <0.07* | 677 ± 32* | – | 6.4 ± 0.4 | – | 1.5 ± 0.1 | – | 121 ± 7* | | μg/g; *ng/g dry wt | Smichowski et al. (2006) |
| | | South Shetland Islands | 154.97 ± 66.71 | 0.01 ± 0.02 | – | 0.46 ± 0.23 | 5.52 ± 1.97 | – | 1.13 ± 0.40 | 0.04 ± 0.03 | 0.04 ± 0.10 | 104.34 ± 49.70 | μg/g dry wt | Jerez et al. (2013a) |
| | **Penguin Adèlie**; **bone** (*Pygoscelis adeliae*) | South Shetland Islands | 277.18 ± 135.74 | 0.01 ± 0.004 | – | 1.06 ± 0.77 | 57.81 ± 35.82 | – | 10.57 ± 8.76 | 0.41 ± 0.41 | 0.04 ± 0.10 | 227.01 ± 121.11 | μg/g dry wt | Jerez et al. (2013a) |
| | **Penguin Adèlie**; **feathers** (*Pygoscelis adeliae*) | Antarctic Peninsula | 59.74 ± 45.26 | 0.04 ± 0.02 | – | 6.37 ± 5.6 | 13.41 ± 2.6 | – | 1.3 ± 1.16 | 0.55 ± 0.55 | 0.64 ± 1.09 | 82.45 ± 13.10 | μg/g dry wt | Jerez et al. (2011) |
| | | Terra Nova Bay | – | – | – | – | – | 0.82 ± 0.13 | – | – | – | – | | Bargagli (2001) |
| | | Admiralty Bay | 87 | – | – | – | – | 1401.4* | – | – | – | 61.5 | μg/g; *ng/g | Santos et al. (2006) |
| | | South Shetland Islands | 79.80 ± 62.22 | 0.13 ± 0.08 | – | 0.18 ± 0.12 | 13.32 ± 8.22 | – | 2.01 ± 0.52 | 0.05 ± 0.03 | 0.24 ± 0.38 | 61.11 ± 20.30 | μg/g dry wt | Jerez et al. (2013a) |
| | **Chinstrap penguin**; **kidney** (*Pygoscelis antarctica*) | South Shetland Islands | 397.49 ± 82.35 | 0.54 ± 0.29 | – | 0.75 ± 0.54 | 13.64 ± 2.28 | – | 10.19 ± 2.63 | 0.08 ± 0.06 | 0.14 ± 0.02 | 92.83 ± 32.19 | μg/g dry wt | Jerez et al. (2013a) |
| | **Chinstrap penguin**; **liver** (*Pygoscelis antarctica*) | South Shetland Islands | 2075.44 ± 1745.28 | 0.11 ± 0.08 | – | 1.11 ± 0.95 | 95.10 ± 48.67 | – | 11.42 ± 3.24 | 0.07 ± 0.07 | 0.18 ± 0.02 | 132.20 ± 64.40 | μg/g dry wt | Jerez et al. (2013a) |
| | **Chinstrap penguin**; **muscle** (*Pygoscelis antarctica*) | South Shetland Islands | 328.59 ± 102.73 | 0.01 ± 0.01 | – | 1.49 ± 0.55 | 6.82 ± 1.20 | – | 2.55 ± 1.53 | 1.83 ± 2.67 | 0.20 ± 0.06 | 105.08 ± 55.41 | μg/g dry wt | Jerez et al. (2013a) |
| | **Chinstrap penguin**; **bone** (*Pygoscelis antarctica*) | South Shetland Islands | 117.49 ± 40.10 | 0.004 ± 0.001 | – | 0.20 ± 0.12 | 0.71 ± 0.36 | – | 12.50 ± 2.13 | 3.82 ± 2.52 | 0.14 ± 0.02 | 235.01 ± 40.62 | μg/g dry wt | Jerez et al. (2013a) |
| | **Chinstrap penguin**; **feathers** (*Pygoscelis antarctica*) | South Shetland Islands | 173.86 ± 173.09 | 0.02 ± 0.03 | – | 0.68 ± 0.49 | 18.57 ± 2.78 | – | 2.25 ± 3.17 | 0.13 ± 0.10 | 0.06 ± 0.04 | 94.99 ± 5.29 | μg/g dry wt | Jerez et al. (2013a) |
| | | Antarctic Peninsula | 164.26 ± 149.75 | 0.1 ± 0.05 | – | 8.08 ± 9.10 | 19.23 ± 3.65 | – | 3.26 ± 2.68 | 1.18 ± 1.1 | 1.76 ± 1.74 | 97.27 ± 21.35 | μg/g dry wt | Jerez et al. (2011) |
| | **Gentoo penguin**; **kidney** (*Pygoscelis papua*) | South Shetland Islands | 302.35 ± 103.68 | 0.20 ± 0.05 | – | 0.21 ± 0.14 | 14.26 ± 4.33 | – | 7.54 ± 3.47 | 0.06 ± 0.05 | 0.0008 | 125.43 ± 12.60 | μg/g dry wt | Jerez et al. (2013a) |
| | **Gentoo penguin**; **liver** (*Pygoscelis papua*) | South Shetland Islands | 854.55 ± 136.61 | 0.08 ± 0.04 | – | 0.18 ± 0.08 | 142.40 ± 63.85 | – | 10.51 ± 3.74 | 0.01 ± 0.01 | 0.0008 | 152.91 ± 45.53 | μg/g dry wt | Jerez et al. (2013a) |

(continued)

**Table 3c** (continued)

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Gentoo penguin**; **muscle** (*Pygoscelis papua*) | South Shetland Islands | 180.07 ± 81.65 | 0.01 ± 0.01 | – | 0.94 ± 0.56 | 4.43 ± 1.46 | – | 1.46 ± 0.43 | 0.04 ± 0.01 | 0.0008 | 106.60 ± 37.42 | µg/g dry wt | Jerez et al. (2013a) |
| | **Gentoo penguin**; **bone** (*Pygoscelis papua*) | South Shetland Islands | 154.13 | 0.001 | – | 0.57 | 0.79 | – | 11.01 | 3.37 | 0.19 | 184.11 | µg/g dry wt | Jerez et al. (2013a) |
| | **Gentoo penguin**; **feathers** (*Pygoscelis papua*) | Antarctic Peninsula | 77 ± 134.55 | 0.03 ± 0.04 | – | 2.71 ± 3.13 | 16.44 ± 3.16 | – | 1.8 ± 1.28 | 0.57 ± 0.35 | 0.51 ± 0.46 | 85.12 ± 14.84 | µg/g dry wt | Jerez et al. (2011) |
| | | South Shetland Islands | 42.85 ± 37.05 | 0.06 ± 0.04 | – | 0.13 ± 0.06 | 6.87 ± 1.54 | – | 0.95 ± 0.69 | 0.01 ± 0.01 | 0.87 ± 0.86 | 80.59 ± 10.85 | µg/g dry wt | Jerez et al. (2013a) |
| | | Admiralty Bay King George Island | 434 | – | – | – | – | 540.9* | – | – | – | 90.7 | µg/g; *ng/g | Santos et al. (2006) |
| | **Snow petrel**; **feathers** (*Pagodroma nivea*) | Terra Nova Bay | – | – | – | – | – | 0.5 ± 0.18 | – | – | – | – | µg/g dry wt | Bargagli (2001) |
| | **Kelp gull**; **feathers** (*Larus dominicanus*) | Admiralty Bay King George Island | 291 | – | – | – | – | 2426.6* | – | – | – | 93.5 | µg/g; *ng/g | Santos et al. (2006) |
| | **South polar skua**; **feathers** (*Catharacta maccormicki*) | Terra Nova Bay | – | – | – | – | – | 2.91 ± 1.93 | – | – | – | – | µg/g dry wt | Bargagli (2001) |
| | **South polar skua**; **liver** (*Catharacta maccormicki*) | | – | 35 ± 16 | – | – | – | 3.1 ± 2.1 | – | – | – | – | | |
| Marine mammals | **Weddell seal**; **hair** (*Leptonychotes weddelli*) | Admiralty Bay King George Island | 1450 | – | – | – | – | 2060.7* | – | – | – | 137.6 | µg/g; *ng/g | Santos et al. (2006) |
| Flora | **Thallus**<br>**macroalge** (*Himmantothallus grandifolius*) | Windmill Islands | 138 ± 247 | 7.5 ± 8.6 | – | 1.4 ± 0.7 | 3.2 ± 1.5 | – | 6.3 ± 3.2 | 1.8 ± 1 | 6.2 ± 6.3 | 72 ± 33 | µg/g dry wt | Runcie and Riddle (2004) |
| | **Thallus**<br>**macroalge** (*Iridaea cordata*) | | 109 ± 38 | 3.1 ± 0.4 | – | 1.9 ± 0.6 | 19.3 ± 1.5 | 0.09 ± 0.04 | 5.9 ± 1.7 | 1.9 ± 0.4 | 8.3 ± 4.4 | 79 ± 27 | | |
| | **Algae** (*Palmaria decipiens Macrocystis spp. Desmarestia spp.*) | Admiralty Bay | 460–4450 | – | – | – | – | (20.4–47.6)* | – | – | – | 27.7–39.6 | µg/g; *ng/g | Santos et al. (2006) |
| | **Phytoplankton**<br>*pooled across species* | Windmill Islands | – | 2.1 ± 0.9 | – | – | – | 0.07 ± 0.01 | – | – | – | – | µg/g dry wt | Bargagli (2008) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Antarctic lichens** (*Usnea sphacelata*, *Usnea sphacelata*) | Deception Island | – | 0.01–0.02 | – | – | 3.2–4 | – | – | – | 0.1–0.7 | – | μg/g | Mão de Ferro et al. (2013) |
| | **Antarctic mosses** (*Polytrichum strictum*, *Sanionia georgicouncinata*) | | – | 0.17–0.23 | – | – | 42–65 | – | – | – | 3.1–4.5 | – | | |
| | **Antarctic mosses** (*Sanionia uncinata*) | King George Island | – | – | 3 ± 1 | 4 ± 1–9 ± 2 | 6 ± 1–19 ± 3 | – | 160 ± 17–390 ± 40 | – | 4 ± 1–19 ± 3 | 25 ± 4–41 ± 7 | μg/g dry wt | Osyczka et al. (2007) |
| | **Antarctic lichens** (*Usnea antarctica*, *Usnea aurantiacoatra*) | | – | – | 2 ± 1 | 2 ± 1–9 ± 2 | 2 ± 1–98 ± 12 | – | 13 ± 2–180 ± 16 | – | 1 ± 1–6 ± 1 | 19 ± 3–35 ± 6 | | |
| | **Antarctic mosses** (*Bryum spp. Polytrichum spp.*) | Admiralty Bay | 3040–4348 | – | – | – | – | (23.1–39.5)* | – | – | – | 18.1–28.0 | μg/g; *ng/g | Santos et al. (2006) |
| | **Antarctic lichens** (*Usnea spp.*) | King George Island | 139 | – | – | – | – | 36.3* | – | – | – | 5.6 | | |
| | **Poaceae** (*Deschampsia antarctica*) | | 610 | – | – | – | – | 67.7* | – | – | – | 44.2 | | |
| Heavy metals in abiotic samples | | | | | | | | | | | | | | |
| Type of sample | | Localization | Range or average concentrations (± standard deviation, if available) | | | | | | | | | | Unit | Lit |
| | | | Fe | Cd | Co | Cr | Cu | Hg | Mn | Ni | Pb | Zn | | |
| Data reported in 80th years and earlier | | | | | | | | | | | | | | |
| Fresh water (lakes) | | South Victoria Land | 640–1480 | – | 348 | – | 220 | – | 23–8760 | 1800 | $<30^3$ | 150 | μg/L | Burton (1981) |
| | | Vestfold Hills | – | 5.3 | – | – | 14.3 | – | – | – | 4.4 | – | | |
| | | Lutzow-Holm Bay | 65–220 | 0.2–5.3 | – | – | 3.5–8.8 | – | 3–12 | – | 1.2–4.9 | 7–118 | | |
| Snow | | Queen Maud Land | $(0.5–1.5) \times 10^3$ | <0.2–3 | – | 0.8–15 | <11–30 | – | – | 4.8–40 | 3–40 | 30–500 | pg/g | Völkening and Heumann (1988) |
| Sediments | | Ross Sea | – | – | – | 47.0 | 25 | – | – | 23.0 | 15.0 | 50 | μg/g | Merlin et al. (1989) |
| | | McMurdo Area | 241–808 | – | – | – | – | $14 \times 10^6$–$79 \times 10^6$ | – | – | – | – | mmol/kg | Siegel et al. (1981) |

(continued)

**Table 3c** (continued)

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data reported from 1990 up to 1999 | | | | | | | | | | | | | |
| Air (aerosol particles) | Antarctic Ocean | 502–9550 | 1.3–41.6 | – | 16–218 | – | – | – | 78–224 | 14.2–75.8 | – | pg/m$^3$ | Riidlein and Heumann (1995) |
| Snow and firn | Dolleman Island | – | 0.08 | – | – | 4 | – | – | – | – | 0.4 | μg/g | Suttie and Wolff (1992) |
| | Adelie Land | – | 0.3 | – | – | 5 | – | – | – | – | 4 | μg/g | Görlach and Boutron (1992) |
| | Coats Land; Queen Maud Land | – | 0.1 | – | – | 3.5 | – | – | – | – | 1.5 | μg/g | Wolff et al. (1999) |
| Surface snow | Dome C | – | – | – | – | – | 0.13–0.50 | – | – | – | – | pg/g | Vandal et al. (1995) |
| Snow pit | Victoria Land | – | – | – | – | – | 0.07–0.71 | – | – | – | – | pg/g | Capelli et al. (1998) |
| Precipitation (snow) | Lake Hoare | – | – | – | – | – | 0.5–5 | – | – | – | – | pM | Vandal et al. (1998) |
| Fresh water | | – | – | – | – | – | 3.3–6.8 | – | – | – | – | | |
| Seawater | Weddel Sea | – | 45–102 | – | – | 162–358 | – | – | – | 87–461 | – | ng/L | Niemistö and Perttilä (1995) |
| Glacial streams | Lake Hoare | – | | – | – | – | 2.7–4.8 | – | – | – | – | pM | Vandal et al. (1998) |
| Ice cores | Law Dome | – | 0.11–0.63 | – | – | 0.06–0.45 | – | – | – | 0.58–4.5 | 0.42–<100 | pg/g | Hong et al. (1998) |
| | Dome C | – | – | – | – | – | 0.19–2.21 | – | – | – | – | pg/g | Vandal et al. (1995) |
| Soil | Antarctic Peninsula | – | 1.0–8.0 | 1.2–28 | 17–86 | 63–570 | – | 329–1138 | 2.9–47 | <14–82 | 40–1301 | μg/g | Carrasco and Prendez (1991) |
| | northern Victoria Land | 12,760–48,540 | 0.05–0.37 | – | 8–68 | 7–37 | 0.01–0.09 | 77–1356 | 3–29 | 4.5–36 | 29–121 | μg/g | Bargagli et al. (1995) |
| | Victoria Land | 3.16 ± 0.67 | 0.21 ± 0.19 | – | 56.8 ± 27.0 | 38.0 ± 42.0 | – | 546 ± 156 | – | 11.3 ± 7.05 | 1.9 ± 21.8 | μg/g dry wt | Bargagli et al. (1999) |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sediment | Chinese Great Wall station | – | – | – | 16–23 | – | – | – | – | – | 41–73 | µg/g | Yuguang and Junlin (1991) |
| | Terra Nova Bay | 37 300 ± 14 400 | 1.96 ± 3.89 | – | 48.1 ± 9.2 | – | – | 915 ± 350 | 16.1 ± 2.7 | 23.5 ± 20.1 | 100 ± 24.5 | µg/g | Giordano et al. (1999) |
| | Terra Nova Bay | 1.64 | – | – | 20.3 | – | – | 359 | 6.3 | 20.7 | 42 | µg/g | Ciaralli et al. (1998) |
| | Italian station, Terra Nova Bay | – | – | – | 21–328 | – | – | – | – | – | – | µg/g | Crespi et al. (1993) |
| | Weddel Sea | – | 0.04–0.72 | – | 91–146 | 31–44 | 0.014–0.044 | 464–660 | 53–63 | 7–9 | 78–89 | ng/g | Niemistö and Perttilä (1995) |
| | King George Island | 2.42 | – | – | 7.6 | 77 | – | 640 | 15.4 | 8.7 | 69 | µg/g | Ahn et al. (1996) |
| | | 2.37 | – | – | 2.6 | 52 | – | 280 | 11.5 | 121.0 | 74 | µg/g | Alam and Sadiq (1993) |
| | | 6.28 | – | – | – | 68 | – | – | 41.3 | 14.9 | 60 | µg/g | Santos et al. (2005) |
| | McMurdo Station | – | – | – | – | 11 | – | – | 68.0 | 7.0 | 32 | µg/g | Lenihan (1992) |
| Volcanic rocks | King George Island | 2.79 | – | – | – | 111 | – | 1500 | 12.5 | 7.7 | 66 | µg/g | Santos et al. (2005) |
| Data reported from 2000 up to 2014 | | | | | | | | | | | | | |
| Air | Terra Nova Bay | – | – | – | – | – | 0.29–2.3 | – | – | – | – | ng/m$^3$ | Sprovieri et al. (2002) |
| Fresh water | Deception Island | – | 0.019 | – | – | 0.078 | – | – | – | 0.049 | – | µg/L | Mão de Ferro et al. (2013) |
| Snow | Princess Elizabeth Land | – | – | – | – | – | – | – | – | 503–1158 | – | pg/g | Edwards et al. (2001) |
| | Ross Sea | – | – | – | – | – | – | – | – | 749–982 | – | | |
| | Dumont d'Urville Sea | – | – | – | – | – | – | – | – | 42–85 | – | | |
| | Prydz Bay | – | – | – | – | – | – | – | – | 376–727 | – | | |
| | Coats Land | – | 0.03–0.8 | 0.1–1.2 | 0.09–7.3 | 0.7–11.9 | – | 0.03–26 | – | 0.1–10.3 | 0.2–10.8 | pg/g | Planchon et al. (2002) |
| | | – | – | – | 0.1–5.2 | 0.7–12 | – | 0.3–25 | – | 0.1–10 | – | pg/g | Planchon et al. (2001) |

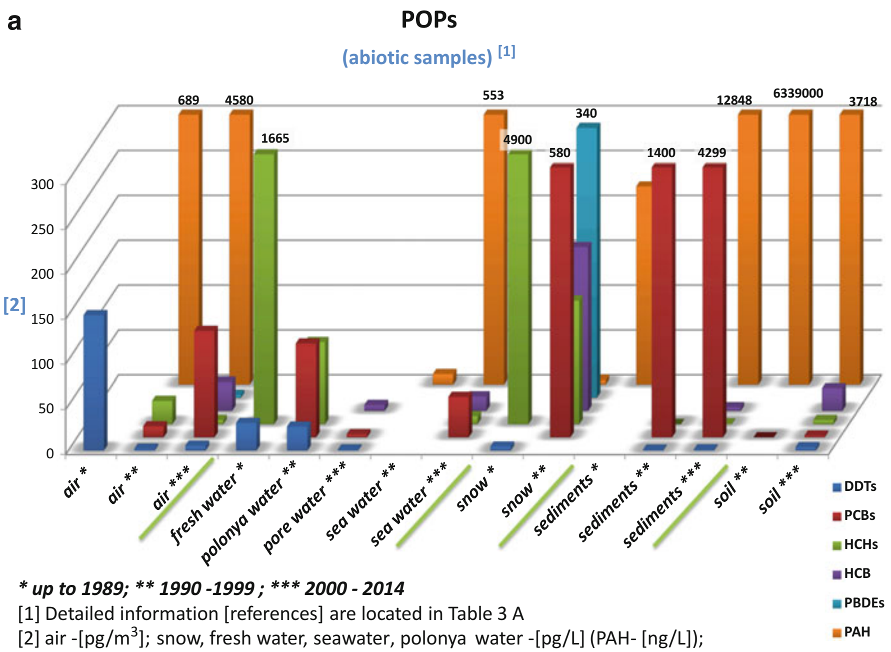
(continued)

**Table 3c** (continued)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Surface snow | Ingrid Christensen Coast, East Antarctica | 0.23–2.88 | – | 0.01–0.18 | 0.04–0.55 | 0.14–4.6 | – | 0.04–1.66 | – | – | 1.31–14.45 | μg/L | Thamban and Thakur (2013) |
| Snow pit | Antarctic Taylor Valley glaciers (Commonwealth, Canada, Howard) | – | <0.057–0.53 | – | – | <0.56–190 | – | – | – | 0.029–13 | – | nM | Fortner et al. (2011) |
| | Glacier, Taylor Valley, Victoria Land | – | – | – | – | – | 0.3–40 | – | – | – | – | pg/g | Witherow and Lyons (2008) |
| | Dome Fuji | – | – | – | – | – | <0.32–2.93 | – | – | – | – | pg/g | Han et al. (2013) |
| | Victoria Land | – | – | – | – | – | – | – | – | 1.5–21.2 | – | pg/g | Velde et al. (2005) |
| Firn core | Victoria Land | – | – | – | – | – | – | – | – | 1.1–10.3 | – | pg/g | Velde et al. (2005) |
| Ice core | Law Dome; Wilkes Land | – | – | – | – | – | – | – | – | 0.08–5.2 | – | pg/g | Burn-Nunes et al. (2011) |
| | | – | – | – | – | – | – | – | – | 0.5–124 | – | nM | Edwards et al. (2006) |
| | | – | – | – | – | – | – | – | – | 0.21–7.00 | – | pg/g | Vallelonga et al. (2002) |
| | Dome C | – | – | – | – | – | <1–65 | – | – | – | – | pg/g | Jiratu et al. (2009) |
| | | – | – | – | – | – | – | – | – | 0.36–13.4 | – | pg/g | Vallelonga et al. (2010) |
| Sediments | Ferraz station, The King George Island | 6.15 | – | – | 40 | 44 | – | 442 | 5.1 | 11.5 | 52 | μg/g | Santos et al. (2005) |
| | | – | – | – | 25–52 | – | – | – | – | – | 87–134 | μg/g | Santos et al. (2007) |
| | Admirality Bay | – | 0.4–0.9 | – | 7–12 | 47–84 | – | – | 3–10 | 3–11 | 44–89 | μg/g | Ribeiro et al. (2011) |
| | | – | – | – | – | 80–91 | – | – | – | – | 50–57 | μg/g | Ribeiro et al. (2010) |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Princess Regnheld Coast | – | – | – | 40–342 | – | – | – | – | – | 26–134 | μg/g | Waheed et al. (2001) |
| | McMurdo Sound | – | 0.03–0.46 | – | – | 0.9–100 | <0.001–0.087 | – | – | 0.34–12.5 | 17–156 | ng/g | Negri et al. (2006) |
| | Ross Sea | – | 0.1–1.6 | – | 12–97 | 10–38 | – | – | 10–46 | 4–20 | 52–144 | μg/g | Ianni et al. (2010) |
| | Amanda Bay, East Antarctic | – | – | – | – | 22.3–35.3 | 55.5–281* | – | – | 20.5–23.8 | 138–652 | μg/g, *ng/g | Huang et al. (2014) |
| | Antarctic Station, Casey | – | – | – | – | – | – | – | – | 5–26 | – | μg/g | Townsend and Snape (2008) |
| | Prydz Bay | – | 0.254–0.421 | – | – | – | – | – | – | – | 34.6–96.6 | μg/g | Sun et al. (2013) |
| | Potter Cove | 32,800–34,100 | 0.56–0.69 | – | 4.2–6.5 | 54–82 | – | 690–700 | – | 4.9–5.8 | 52–63 | μg/g | Vodopivez et al. (2015) |
| | | 19,665 | 0.25 | – | 7.0 | 103 | – | 798 | – | 7.6 | 56 | | Curtosi et al. (2010) |
| | | 5.15–21.39 | – | – | 4.11–8.11 | 73.37–156.3 | – | 0.79–1.13* | – | 2.29–5.52 | 44–96–63.02 | μg/g; *mg/g | Andrade et al. (2001) |
| Soils | near Lake Vanda | 1.00 | – | – | – | 28 | – | 104 | 11.2 | 3.9 | 24 | μg/g | Webster et al. (2003) |
| | Fildes Peninsula, King George Island, | 43,255–70,534 | 0.04–0.34 | – | 17.10–64.90 | 51.10–176.50 | 0.0081–0.0601* | 449–1401 | 7.18–25.03 | 2.76–60.52 | 41.57–80.65 | μg/g, *ng/g | Lu et al. (2012) |
| Volcanic rocks | The King George Island | 2.92 | – | – | – | – | – | 1100 | 60.7 | – | – | μg/g | Machado et al. (2001) |

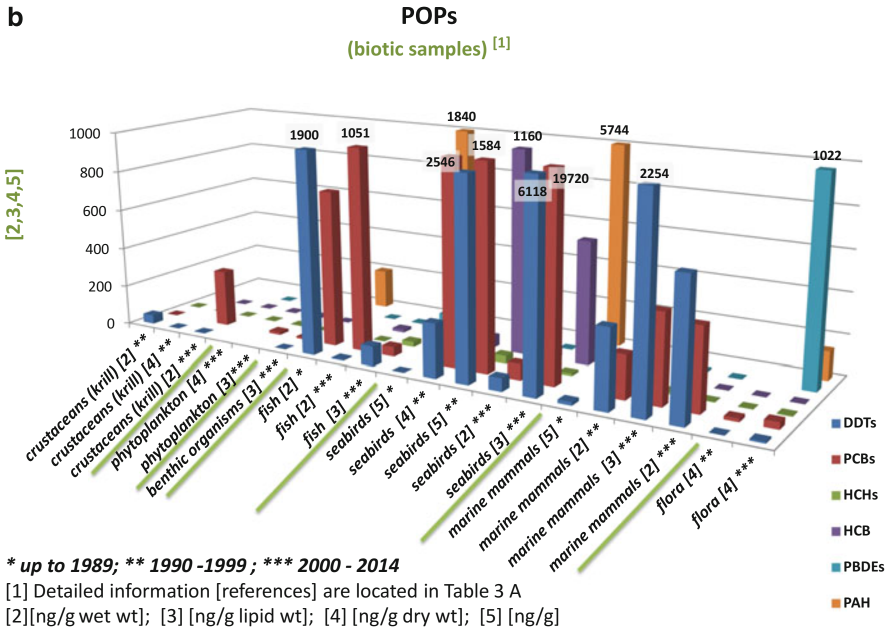
[e] LOD—limit of detection



**** up to 1989; ** 1990 -1999 ; *** 2000 - 2014***

[1] Detailed information [references] are located in Table 3 A

[2] air -[pg/m$^3$]; snow, fresh water, seawater, polonya water -[pg/L] (PAH- [ng/L]); soil, sediments - [ng/g]



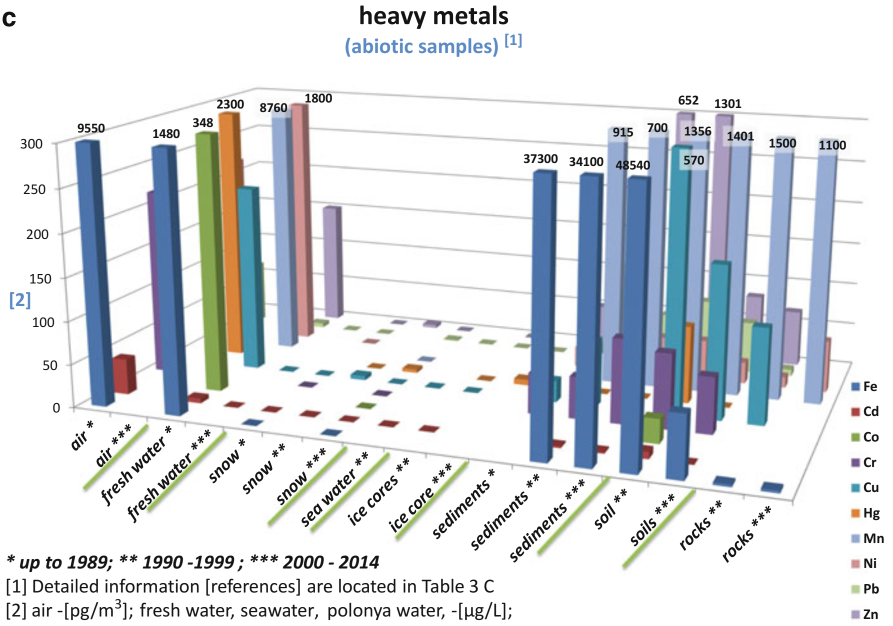
**** up to 1989; ** 1990 -1999 ; *** 2000 - 2014***

[1] Detailed information [references] are located in Table 3 A

[2][ng/g wet wt]; [3] [ng/g lipid wt]; [4] [ng/g dry wt]; [5] [ng/g]

**Fig. 4** Contamination concentration levels during three time periods: (a) POPs in abiotic samples, (b) POPs in biotic samples, (c) heavy metals in abiotic samples, (d) heavy metals in biotic samples

**c**

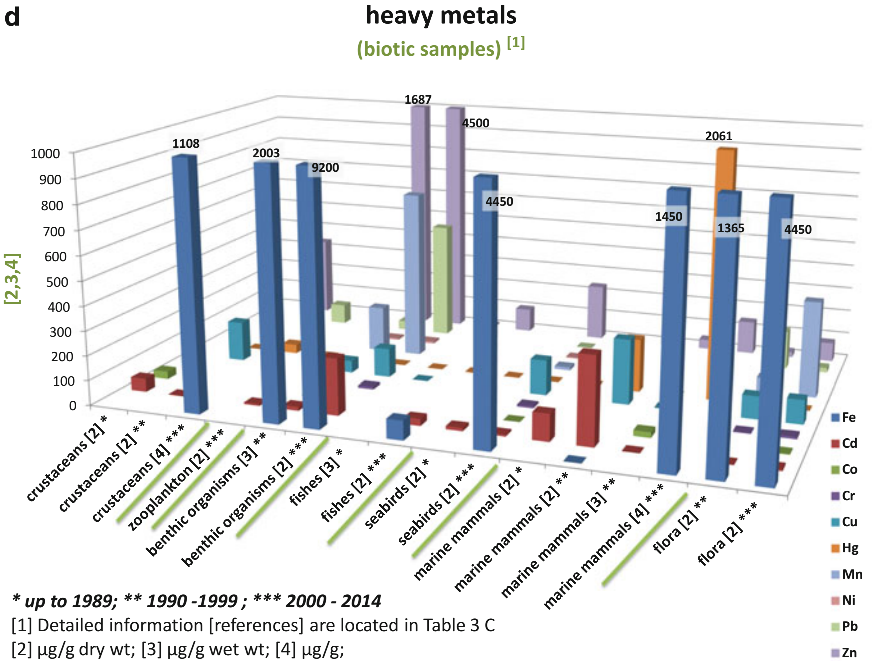


**** up to 1989; ** 1990 -1999 ; *** 2000 - 2014***

[1] Detailed information [references] are located in Table 3 C

[2] air -[pg/m$^3$]; fresh water, seawater, polonya water, -[μg/L]; soil, sediments, rocks, ice cores, snow, - [μg/g] (Hg - [ng/g])

**d**



**** up to 1989; ** 1990 -1999 ; *** 2000 - 2014***

[1] Detailed information [references] are located in Table 3 C

[2] μg/g dry wt; [3] μg/g wet wt; [4] μg/g;

**Fig. 4** (continued)

and activities of tourists and scientists can result in the detectable contaminants (PBDE, PFAS) in most stations' areas in Antarctica (Cai et al. 2012). Every part of the abiotic environment (as well as Antarctica's atmosphere and reservoirs: soil and snow) are currently closely coupled. These parts, affecting each other, have a tendency for re-volatilization of POPs to the atmosphere. These are so called secondary sources of pollution. However it is not known to what extent this remobilization is a part of a seasonal cycle with volatilization during summer and deposition during winter (Cabrerizo et al. 2013). Glacial melt may carry pollutants to nearby lakes and the adjacent coastal marine areas, thereby spreading the contamination and increasing its impacts (Majer et al. 2014). Glacier meltwater can be a current source of pollution to Antarctica's marine food web as a result of an unexpected consequence of climate change (Geisz et al. 2008). Therefore the monitoring and remediation of this scenario is essential. The active layer/permafrost transition zone was revealed to be a low-permeability barrier to downward migration of chemical compounds (Curtosi et al. 2007). Near Antarctica's stations exhibiting PAHs contamination in soils, this behaviour highlights the risk for coastal marine environments (Curtosi et al. 2007). An analysis of stations' emissions and transect sampling of abiotic matrices are carried out. The research provides indication as to the significance of research stations as local sources of POPs contamination (Bengtson Nash et al. 2010). Only few studies have determined PCB and organochlorine pesticides (OCP) concentrations in sediments in Antarctica (Zhang et al. 2013). Pollution in marine sediments are the end result of a long term accumulation and this is not directly correlating with activities on land. Unfortunately, pollutants in sediments will persist for many years to come (Kim et al. 2006), hence it is necessary to control the levels of pollution in every part of abiotic environment including sediments.

Referring to abiotic research the monitoring programs need to be extended to facility points far from major bases, assessing the extent of contamination in order to prevent local pollution episodes. This kind of studies should verify the hypothesis of a decline of PCBs in the last decade in Antarctica (Vecchiato et al. 2015).

In the discussion of biological research, what is important is using organisms for monitoring. Atmospheric monitoring of POPs using conventional instrumental methods is expensive and difficult. Scientists can overcome this limitation using biomonitoring methods and thereby provide reliable information assessing the impact of pollutants on the biota and various ecosystems. Most popular in Antarctica is using mosses to define the relationship between the concentrations of POPs in Antarctic environment and in the atmosphere (Wu et al. 2014). It should be noted, based on PBDEs studies, that mosses can accumulate more POPs than lichens (Yogui et al. 2011).

Equally important is the transport of pollution between organisms. Collected data can be useful to notice that the high concentrations of POPs encountered in the brown skua is certainly correlated to its migratory habits as well as its high trophic level position (Taniguchi et al. 2009). A useful tool to trace migration behaviour of seabirds and marine mammals can be the research of POPs levels in tissues (Kallenborn et al. 2013). Moreover, the transfer of contaminants between

Antarctica's pelagic and benthic organisms is associated with seasonal sea-ice dynamics (Van den Brink et al. 2011). The concentrations of organochlorines in penguin eggs may be toxicologically insignificant, but more studies are needed to assess the real health risks associated with these levels of pollutants because Antarctica's seals and penguins are more sensitive to contaminants than those living in temperate regions (Schiavone et al. 2009b).

In a comprehensive approach to the issue of the presence of pollutants in Antarctica, it is also very important to become familiar with accurate levels of heavy metals in this environment. In a discussion of heavy metals in abiotic environment, the geochemical characteristics of the area should be further investigated, in particular, the transport of metals as particulate or soluble fraction from the terrestrial to the marine environment (Vodopivez et al. 2015). Based on lead isotopic data, Southern South America is an important source of dust deposited in Antarctica's ice (Vallelonga et al. 2010). Moreover, based on results of research on ice cores, anthropogenic activities have become the most important source of heavy metals in Antarctica (Yin et al. 2006). Antarctica is a kind of a sink for heavy metals (e.g. Hg). Considering long atmospheric lifetime and the ability to deposit and be re-emit from soil and oceans, the ability of heavy metals to bioaccumulate suggests that their deposition would indeed have a serious effect for environment (Sprovieri et al. 2002).

Referring to heavy metals present in biological samples, particular attention should be paid to the biomagnification process which depends upon the food web (high trophic level animals have a higher content than lower trophic level ones) (Moreno et al. 1997). The presence of potentially toxic elements (such as Cd and Hg) in penguins suggest, that the accumulation of elements depends on the geochemical characteristics of the area, age of individuals and also on their diet (mainly krill) (Smichowski et al. 2006). Moreover, the results of research indicated, that a slight increase in Mn and Cr levels in Antarctica could be related mainly to human presence (usage of combustibles and oil contamination). Other studies indicate common sources of pollution (such as Cr, Ni, Pb, Mn, Cd or As), which are correlated with anthropogenic activities (plane and ship trips related to the tourism industry) (Jerez et al. 2013a). Feathers can be an important identifiers of the absorbed heavy metals (e.g. Pb) in penguins (Jerez et al. 2013b). For a better understanding of spatio-temporal trends feathers of Antarctic penguins, put together with other penguin tissues, are useful tools for long-term monitoring of trace elements in Antarctic marine environment (Jerez et al. 2011).

Furthermore mercury and its transformation products (e.g. methylmercury), because of their high bioaccumulation properties, should be investigated more precisely. A quantitative understanding of pathways and mechanisms that affect the transport of mercury from sources to ecosystems as well as the conversion of mercury to methylmercury, and their bioaccumulation in food webs are fundamental to evaluating and managing human and wildlife health risks in a local and global scale (Driscoll et al. 2013). The observations that have been made in polar marine ecosystems showed progressive increase in mercury concentrations in the food web (Bargagli et al. 1998). The role of Antarctic coastal ecosystems as sink in the global

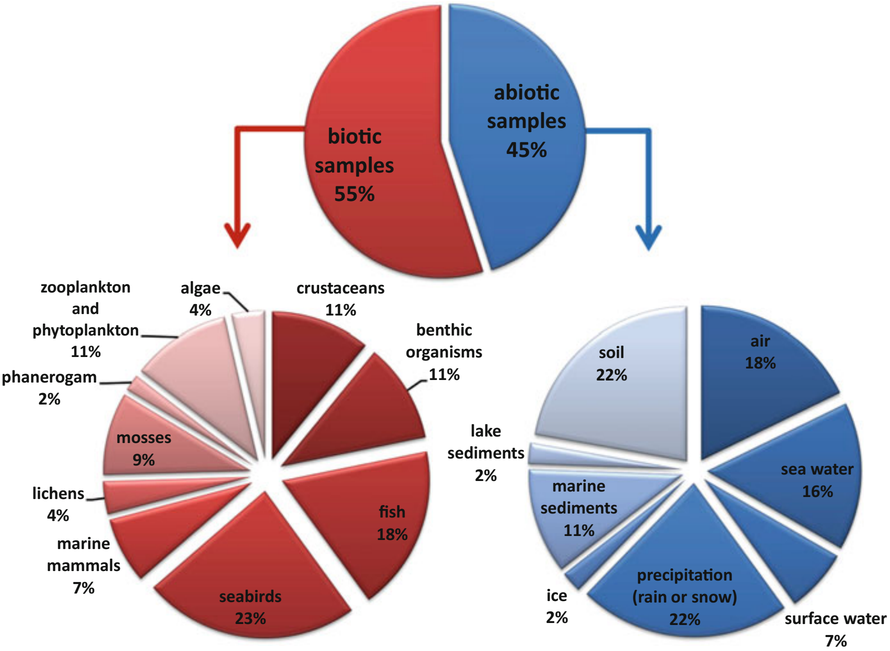


**Fig. 5** Classification of analytical research according to types of environmental samples collected in the years 2000–2014

mercury cycle can be enhanced by the global warming and the possible change in the ice coverage together with increasing anthropogenic emissions of gaseous mercury in countries of the Southern Hemisphere (Bargagli et al. 2007). It clearly demonstrates the need for understanding how climatic variability and anthropogenic disturbances (e.g., increases of population, perturbations to food chains, changes in other air pollutants) affect mercury and methylmercury concentrations in Antarctic ecosystems (Driscoll et al. 2013; Bargagli 2008). Research data on pollutant levels has been enhanced during last two decades. Figure 5 presents information on the proportion of various types of analytical research in a general number of studies aimed at getting to know the degree of pollution of the Antarctica's environment during the last two decades.

The most popular research locations were the areas of the Antarctic Peninsula (including South Shetland Islands) and Ross Sea. A little more attention (55 % of contemporary research) is paid to tests of biological samples, mostly due to the interest in the actual influence of pollutants on Antarctica's ecosystem and becoming familiar with new directions of pollutant movement in the food web. Research on the chemical composition of inorganic samples (45 % of contemporary research), is equally important, as elements of abiotic environmental media are the first link in the pollutant movement process in Antarctica.

## *4.3 Analytical Techniques in the Study of the Antarctic Environment*

Together with the development of science and instruments, various analytical procedures and techniques were used in analytical practice to test environmental samples (abiotic and biotic) collected in Antarctica.

Nowadays, Antarctica's researchers have gained access to many different analytical techniques of scope detection, power and robustness, which they couldn't even dream of some decades ago (Caroli 2001). For the chemical elements they can use: atomic absorption spectrometry (AAS) with flame or electrothermal (another name—graphite furnace (GF)) atomisation, inductively coupled plasma—atomic emission spectrometry (ICP-AES), inductively coupled plasma—optical emission spectrometry (ICP-OES), atomic fluorescence spectrometry (AFS), mass spectrometry (MS) with different ionization sources (e. g. ICP), X-ray fluorescence spectrometry (XRF), neutron activation analysis (NAA), ion-selective electrodes and isotope dilution mass spectrometry (IDMS). For organic substances, depending on properties of organic substances, analysts can choose one of the following techniques: gas chromatography (GC), high performance liquid chromatography (HPLC), thin layer chromatography (TLC), supercritical fluid chromatography (SFC) and gel permeation chromatography (GPC) with several detection systems (electron capture (EC), flame ionization (FI)), thermal conductivity (TC), flame photometry (FP), infrared spectroscopy (IR), UV absorption spectrophotometry, fluorescence (F), capillary zone electrophoresis (CZE) and MS (Caroli 2001). To determine ionic compound concentration the analysts use ion chromatography (IC) with various types of detection (e.g. conductometry detector (CD), ICP).

Applications with impressively high-resolution and full scan performances were made possible by modern instrumental configuration, that is hybrid mass spectrometers. Quantification of highly polar organic pollutants without derivatization, lower than the ppt level (nanogram per liter or per kilogram of matrix) in environmental samples, is possible by the use of tandem mass spectrometry combined with liquid chromatography. The measurement of emerging contaminants in environmental analysis are performed using the achievements of liquid chromatography—mas spectrometry (LC-MS) like the more recent advancements in triple quadrupole (QqQ), linear ion trap, time of flight analyzer (TOF) and Orbitrap mass spectrometers (Magi and Tanwar 2014).

Generally, the analysts are warned of pushing the instrumental method beyond its intrinsic limits, in terms of limits of detection, optimal working range and applicability to specific groups of substances. Otherwise, the rapid increase in the overall uncertainty associated with the experimental date will be observed soon (Caroli 2001).

Polar regions are an excellent place to study some natural phenomena as well as historical trends mostly due to the large distance between them and anthropogenic emissions sources. The concentration of micro-constituents or micro-pollutants in polar regions is rather low and therefore it is necessary to develop some analytical methods of high sensitivity.

The chemical specification of such a variety of samples requires scientific experience and skills from different areas of science. The wide choice of analytical techniques, from the classical to the most innovative ones, which are available nowadays, offers the scientists an opportunity to face challenging qualitative and quantitative determinations. What is more, some more precise chemical information can be achieved by developing hyphenated methodologies, which means the combination of different instrumental techniques (Magi and Tanwar 2014).

Nowadays the most useful analytical tool seems to be the mass spectrometry, which was designed for determining a wide range of compounds present in environmental samples. In combination with such techniques as gas or liquid chromatography, it creates the possibility of specifying the organic (GC-MS, LC-MS) as well as inorganic compounds (ICP-MS) with a large degree of sensitivity and selectivity. Another advantage of such an analytical solution is the fact that MS provides more chemical information using a minimum amount of sample than any other analytical method (Gasparics and Marıa 2000; Magi and Tanwar 2014; Planchon et al. 2001).

Determination of organic contaminants in various matrices is usually performed using chromatographic techniques (Płotka et al. 2013). Actual trend in chromatography is development of multidimentional approaches (e.g. Ouyang et al. 2015; Seeley and Seeley 2013). Multidimensional chromatography is a technique for isolating and identifying volatile (GC) and semi-volatile (GC and LC) organic compounds present in complex mixtures during one analytical cycle. Hence this techniques coupled with mass spectrometry can provide an important tool in a future monitoring of organic chemicals in Antarctica. Therefore, because of a low concentration of chemical compounds in complex matrices (feathers, leathers and internal organs of organisms) (Magi and Tanwar 2014), Antarctica poses a real challenge of developing innovative analytical approaches as well as improving MS instrument performances.

## *4.4 Impact of Research Station Activities on Pollution Levels*

Research stations are and will be an inseparable element of the Antarctic environment. Individual polar stations have a different nature. A detailed description of the operations of polar stations is presented in Table 4. The influence that each station can have on Antarctic environment is related with length of time it has been operated or/and number of people present at station etc. This information is given regularly each year by Council of Managers of National Antarctic Program (COMNAP) on its webpage (e.g. COMNAP Information). It is also important that the development of research (the use of the station and the construction of new facilities) should not additionally contribute to environmental pollution. There are numerous ways of operating stations without polluting the environment. The

**Table 4** Characteristics of polar stations operating in Antarctica (SCAR Information)

| Division according to the infrastructure | |
|---|---|
| Type of infrastructure | Description |
| Station | – consists of durable buildings and mechanical services, |
| | – buildings are equipped with power supply and water and sewage systems |
| Camp | – more basic and less durable sleeping facilities are situated at the camp (tents, shelters), |
| | – these places are often used only for a few seasons, |
| Refuge | – has a permanent nature, |
| | – usually small and easy to install single huts |
| Airfield | – infrastructure (camp or shelter) is situated near the airport, it is usually connected with it, |
| | – not distinguished according to the size |
| Depot | – for storing food, fuel and other things |
| Division according to the specificity of operations | |
| Specificity of operations | Description |
| Year-round | – operate both in summer and in winter |
| Seasonal | – operate in summer |
| Closed | – the facility does not exist any more |
| Temporarily closed | – the facility has been closed on a temporary basis, ready to be re-opened, if necessary |
| Closed stations | – stations closed for an indefinite period of time |
| | – the facility can be renovated and/or re-used at any time |

Princess Elisabeth Antarctica Station is an example of a station that virtually has no impact on the environment. At this station, electricity is produced using photovoltaic panels, solar collectors and wind turbines. The use of renewable sources of energy in Antarctica in the twenty-first century should not be a sign of modernity in this area, but a necessity. Reduction of potential anthropogenic pollution sources to a minimum allows to obtain reliable research results, in particular in research on long-range atmospheric transport of pollutants (Polar Foundation Information). The results of work on the design process of a photovoltaic (PV)-wind power system were recently published. This system could be installed in very challenging ambient conditions. This work has been done in the French-Italian Antarctic Base (Concordia Base). Work in this scope should be continued in other polar bases. Pollution can affect important research activities in this area (e.g. astronomical observations, studies of physics of atmosphere and Earth science). The ambient conditions significantly affect the quality of the research results. Usage of renewable energy leads to reduce usage of diesel generator and thereby leads to preserve an ecosystem, which is mandatory for heritage of the humanity (Boccaletti et al. 2014).

## 5 Summary and Conclusions

The environment of polar regions is characterised by the lowest pollution levels in the world. However, the growing number of studies on the presence of a broad range of chemical compounds in various elements of the Antarctic environment may indirectly indicate the scale of the problem of growing symptoms of global human influence in this area.

Over the past decade, the scope of tested samples has been extended; however, the type of pollutants identified in individual samples (in the years 2000–2014) differs from the previous decades, *inter alia* is enhanced to new emerging pollutants. Most of the information about the presence of pollutants in biotic samples pertains to samples of Antarctic mosses krill, molluscs and invertebrates, various fish species and maritime birds—mostly penguins. Research of biotic samples have a special value as more and more attention is devoted to the phenomenon of bioaccumulation and its consequences within one plant or animal species as well as to biomagnification in the food chain. Research data about pollutants detected in abiotic samples are also important mainly due to direct and continuous contact with Antarctic biota.

A significant part of research is targeted at the occurrence of POPs compounds in the environment (Fuoco et al. 2009a, b). A possibly exhaustive list of information pertaining to POPs present in Antarctica's environment is possible only for several groups of compounds (HCB, PCB, DDTs, PBDE and PAHs). Their presence may largely result from the activity of research stations and the development of tourism. Over the past decades, sporadic research also pertained to identification and determination of compounds, such as: CHL, dioxins, DLC, PFCs, pesticides (dieldrin, mirex, heptachlor, endosulfan), aliphatic hydrocarbons, n-alkanes and cumulative parameters such as TOC in various environmental samples. In the future emerging pollutants exhibiting characteristics of persistence comparable to POPs should also be considered in long term monitoring.

Heavy metals are global pollutants and can reach almost any location on Earth. They come from natural, volcanic or geological sources, or as a result of anthropogenic activities. Accordingly with increasing human presence in Antarctic region the presence of metals in this area is becoming an issue that needs to be more investigated. Especially issues like: understanding of pathways and mechanisms that affect the transport of mercury from sources to ecosystems, the conversion of mercury to methylmercury, and its bioaccumulation state in food webs should be continuously studied.

Regrettably, data on pollutants in Antarctica's environment are dispersed in many magazines. It is worth mentioning that over the years different methods of POPs quantification have been used. Often information is scarce or lacking on the biology of the sampled species (age, sex, nutritional status, reproductive status, etc.). This makes data difficult to compare (Trumble et al. 2012). The fact that research results are presented in various units (g/g wet wt, g/g dry wt., etc.) is a further inconvenience, as it also makes it difficult to compare results of studies conducted in various areas of Antarctica. To overcome this problem, some of scientists have presented their results expressed in multiple units (Court et al. 1997; Yogui et al. 2011); unfortunately very few researchers have done so.

Research on the influence of research stations on the pollution levels in the surrounding environment is also important. Detailed research in this areas leads to differentiate sources of pollutants between influence of local sources and global sources (LRAT). Additionally polar stations should implement usage of renewable energy in whole possible areas. This kind of solution of energy production leads to reduced usage of diesel generators and thereby lead preservation of the polar ecosystem.

The analysis of available information allows for concluding that human activity on a local and global scale leads to affecting and/or degradation of Antarctic ecosystems. The basic direction for contemporary Antarctic research pertaining to pollutants should be:

- carrying out the long term atmospheric monitoring for main POPs and new emerging pollutants coupled with meteorological data,
- carrying out the long-term monitoring of man-made chemicals (as well as new emerging pollutants monitoring) in Antarctic abiotic environment and endemic species in order to follow the future trends of global contamination,
- the detailed description of remobilization processes and "second sources" (e.g. melting glaciers) of pollutant in polar areas,
- the enlargement of research using non-invasive samples (like feathers and preen oil) as a useful tool to POPs and heavy metals monitoring,
- the determination of reaction and tolerance individual pollution levels for Antarctica's fauna and flora towards individual anthropogenic chemicals (examination of the toxicological sensitivity of Antarctic key species),
- the detailed description of environmental fate (including biotic and abiotic environment) and negative effects on Antarctic ecosystem of anthropogenic compounds,
- the development of innovative analytical approaches improving the limits of detection of chemical compounds in various abiotic and biological matrices.

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